407

Frontiers in Artificial Intelligence and Applications

MODERN MANAGEMENT BASED ON BIG DATA VI

Proceedings of the 6th International Conference (MMBD 2025), Hong Kong, 7-9 July 2025

Edited by
A.J. Tallón-Ballesteros

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Frontiers in Artificial Intelligence and Applications

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Preface

MMBD2025, focusing on the general theme of *Big Data and Modern Management* along with cutting-edge research topics, has drawn substantial participation from professors and postgraduate students – particularly PhD scholars – from universities worldwide, as well as technicians, policymakers, and senior executives from diverse industries and organizational sectors. The accepted papers primarily address the following key areas: innovation in online education management driven by big data, green supply chain management, big data analytics in supply chains, sustainable development decision-making, digital economy, platform economy, digital innovation, social strategies for human relationship management, total quality management, and modern hospitality and tourism management.

This conference proceedings is structured in three parts:

- Part I: Modern Management and Big Data
- Part II: Interdisciplinary Field of Modern Management and Big Data
- Part III: Special Session on Lifelong Education

All submissions have undergone rigorous and meticulous review by members of the international Technical Program Committee (TPC) and anonymous reviewers, ensuring alignment with MMBD's research scope in terms of both thematic breadth and analytical depth. From approximately 193 submissions, 58 high-impact contributions representing the most promising advancements in the field and with strong relevance to the series *Frontiers in Artificial Intelligence and Applications (FAIA)* were selected for inclusion.

We would like to extend our sincere gratitude to all keynote speakers, invited presenters, authors, TPC members, and anonymous reviewers whose dedicated efforts have been instrumental in the success of the conference. We would also like to acknowledge the editorial team and colleagues at IOS Press for their collaborative work in publishing this volume as the sixth edition of the MMBD conference series within the FAIA book series.

Finally, we mourn the unexpected loss of Dr. Einar Fredriksson, founder of IOS Press, who passed away on April 30, 2025. His vision and leadership profoundly impacted the academic publishing community, and his legacy will continue to inspire our work.

July 2025

Antonio J. Tallón-Ballesteros
University of Huelva (Spain)
Huelva City, Spain

About the Conference

Co-hosted by Xiangnan University, the 6th International Conference on Modern Management based on Big Data (MMBD2025) will be held in hybrid format (onsite in Hong Kong and online) from 7–9 July 2025. MMBD2025 features core themes centered on modern management and big data, complemented by cutting-edge research topics and dedicated sessions, including:

- A special session on big data-driven manufacturing and service industry supply chain management
- A special session on lifelong education supported by the Hunan Lifelong Education Research Base (Xiangnan University Base)
- A track on applied education and applied research in AI, data science, and Web 6.0, proposed and chaired by Dr. Adela Lau from the HKU SAAS Data Science Lab, School of Computing and Data Science, The University of Hong Kong.

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Part I

Modern Management and Big Data

Modern Management based on Big Data VI
A.J. Tallón-Ballesteros (Ed.)

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Analysis of the Price Volatility in the CSI 300 Stock Index Futures Based on the GARCH Model

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Abstract. As a crucial tool for investors to carry out risk hedging and other investment operations, stock index futures have garnered significant attention and analysis from scholars both domestically and internationally. The article uses EViews software to study the price volatility characteristics of CSI 300 stock index futures. Firstly, the article analyzes the distribution characteristics and trends of its price and yield, and conducts stability test and ARCH effect test on the price and its logarithmic yield. Finally, a GARCH model is constructed to empirically analyze the volatility characteristics of the yield series. The article reveals that the yield series of CSI 300 stock index futures exhibits significant characteristics of volatility aggregation and persistence. This finding offers investors valuable information for pre-investment analysis.

Keywords. Stock index futures; GARCH model; Volatility; Feature analysis

1. Introduction

The constituents of CSI 300 Index cover a wide range of industries in Shanghai and Shenzhen, almost all important industry sectors in the market, and can fully reflect the overall price trend of China's A-share market. As the first stock index futures launched in China, CSI 300 stock index futures have become an important financial derivative tool in China's financial market. It took only three years for it to leap to become the second largest stock index futures in the world. At present, a considerable number of articles have employed the GARCH model to investigate the volatility of financial markets. However, these studies primarily concentrate on the correlation between price volatility in stock index futures and the spot market, as well as on driving factors and price discovery functions. Consequently, there is a relative scarcity of analyses focusing specifically on the price volatility characteristics inherent to stock index futures themselves. Therefore, the article selects the price data of the main contract of CSI 300 stock index futures since the launch of CSI 300 stock index futures and establishes a GARCH model to analyze its price volatility characteristics, aiming to provide some basic research results for the risk management and investment strategy of CSI 300 stock index futures. Specifically, in terms of risk management, the findings of this study help manage the trading risk of CSI 300 stock index futures. Due to the leveraged nature of

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stock index futures trading, the returns and risks of its trading are magnified. Therefore, mastering the characteristics of volatility changes in stock index futures will be timely and effective in avoiding trading risks. Especially when implementing volatility trading, the findings of this study help the investor to grasp the effective stock index futures volatility pattern and avoid the loss caused by abnormal volatility risk. Meanwhile, in terms of investment strategies, the results of this study help to construct trading strategies related to stock index futures, which provide a reference for quantitative traders to identify dynamic price fluctuation risks at any time in the complex financial market, accurately capture the deterministic components in the stochastic volatility of stock index futures, and deepen the understanding of the market volatility trends and patterns.

2. Theoretical foundations

2.1. Characteristics of Stock Index Futures Volatility

Stock index futures prices are a nonlinear, non-stationary and high signal-to-noise time series [1]. There are many studies on volatility, mainly focusing on the following aspects. Volatility in the stock and futures markets is characterized by sharp peaks and thick tails, i.e., the time series of the stock market has thicker tails on both sides relative to the normal distribution [2]. There is an aggregation characteristic of volatility in the stock [3] and futures markets, and when volatility arises, it tends to show a positive correlation [4]. In addition to aggregation, asymmetric fluctuations between futures and stock markets can cause fluctuations that negatively affect prices to be larger than those that positively affect them, and there is also persistence in fluctuations, so that when larger fluctuations are generated, this fluctuation does not disappear quickly but continues to have an impact on stock or futures prices and yields for some time in the future[5].

2.2. Volatility-related theories

Volatility refers to the situation in which a random variable moves with the time variable, so how to measure volatility is an important topic when studying the volatility characteristics of a time series. Since the article uses the time series of daily returns of CSI 300 stock index futures, the simplest case is that the time series variance is constant. Therefore, based on the assumption that the variance of the time series is constant, there are three basic methods to measure the volatility [6][7]. Firstly, the extreme value difference method, which can effectively and intuitively express the overall change and distribution range of the time series, but lacks the precision and comparability of the detailed description. The second is the spread rate method, which is based on the extreme value spread method, and measures the volatility of the time series through the relative change amplitude, which corrects the problem of insufficient comparability in the extreme value spread method. The third method is the standard deviation approach, which quantitatively describes the magnitude of risk and plays a crucial role in assessing the return and risk associated with financial assets. This method has been widely adopted for measuring the volatility of financial series.

3. Data analysis

3.1. Data sources and modeling

The article selects the CSI 300 stock index futures as the research object, obtaining the closing prices of the main futures contracts from April 16, 2010, to January 2, 2024, from the RESSET database, totaling 3,334 closing price data. All analyses in the article are completed using EViews software.

The GARCH model is an optimized statistical model of the ARCH model, and the introduction of the GARCH model alleviates to some extent the problem of reduced efficiency of the ARCH model in the presence of high-order autocorrelation. Among GARCH models, the most widely used is the GARCH(1,1) model, which has a lag order of 1 for both the autoregressive and moving average terms [8]. For a time series rt, the standard GARCH(1,1) model is:

$$y_t = y_{t-1}'\gamma + u_t, \quad t = 1,2,\cdots,T \tag{1}$$

$$\sigma_t^2 = \omega + \alpha u_{t-1}^2 + \beta\sigma_{t-1}^2 \tag{2}$$

Where $y_{t-1} = (x_{1t-1}, x_{2t-1}, \cdots, x_{kt-1})'$ is the vector of explanatory variables and $\gamma = (\gamma_1, \gamma_2, \cdots, \gamma_k)'$ is the vector of coefficients. The mean equation σ_t^2 is a function of the exogenous variables with a disturbance term. This conditional variance consists of three components, the constant term, the lagged term using the square of the perturbation term of the mean equation, and the predicted value of the variance in the previous period.

3.2. Descriptive statistics

Firstly, the price of CSI 300 stock index futures is plotted on a chart, as shown in Figure 1, it is clear that the price of CSI 300 stock index futures is not a smooth time series, and the daily closing price of CSI 300 stock index futures is basically in the range of 2,000 to 3,500 points in the period of 2010-2014. After 2014, the daily closing price of the CSI 300 stock index futures showed a more pronounced increase and reached its first peak in 2015 with a closing price of over 5,000. The price of the CSI 300 stock index futures then fell back to near 3,000 in 2016, before fluctuating around 3,500 to 4,000 between 2017 and 2018 and remaining between 3,500 and 4,000 from 2018-2020. Beginning in 2020, the CSI 300 stock index futures' prices again showed substantial growth and at one point surged to 5,500 points. In the following year, the price of CSI 300 stock index futures basically remained in the range of 4,500 to 5,000 points until 2021 onwards, when the price of CSI 300 stock index futures fell back to 4,000 points, and in 2023, fell further to 3,500 points. The price trend of CSI 300 stock index futures illustrates that after volatility occurs, the futures price does not immediately detach itself from the volatile state and become smooth, but continues to fluctuate for a period of time, so it is possible and necessary to study the volatility of CSI 300 stock index futures.

The descriptive statistics of futures prices are calculated, and the results are shown in Table 1, the mean of the closing price of CSI 300 stock index futures is 3488.71, the median is 3466.8, and the standard deviation is 828.53, with a large standard deviation, indicating that there is a large gap between the individual data values of the data and the mean, and that the distribution of the price is more loosely distributed, with a high degree of dispersion and higher price volatility. The skewness of the closing price of CSI 300 stock index futures is 0.28, which indicates that the price data is overall right skewed with a longer right tail; the kurtosis is 2.41, which indicates that the overall distribution of the price data is characterized by a short-peak distribution compared to the normal distribution, implying that the distribution curve of the CSI 300 stock index futures is flatter compared to the normal distribution, the peak is not as pronounced as that of the normal distribution, and the range of the data distribution is relatively wider and the data The value of J-B statistic is 91.21 and the P value is 0, which means that the hypothesis of normal distribution of CSI 300 stock index futures price series is rejected at 1% confidence level, indicating that the CSI 300 stock index futures price series do not obey normal distribution.

Figure 1. CSI 300 Stock Index Futures Price Chart

Before testing the ARCH effect on the yield series, it is necessary to take the logarithmic difference of the price of CSI 300 stock index futures to get its yield data, which can effectively weaken the fluctuation amplitude and abnormal fluctuations in the price series of CSI 300 stock index futures and make the data more stable. Descriptive statistics are calculated for the daily yield data, and the results are shown in Table 1. According to the results of the descriptive statistics of the daily yield, it can be found that the mean of the yield data is -0.000242, which is close to 0, the median is -0.02, and the standard deviation is 1.54. Compared with the descriptive statistics of the price series, the standard deviation of the yield series is relatively small, indicating that the yield series is more stable than the price data, and therefore the results obtained through the regression of the yield data are more credible than those obtained through the regression of the price data. The skewness of the yield series is -0.39, which indicates that the distribution pattern of the yield data is left-skewed, i.e., the left tail is longer, indicating that most of the daily yields are concentrated in the negative range. Its kurtosis is 10.37, which indicates that the yield data have obvious spike distribution characteristics, and most of the data are concentrated in a relatively small range with less variability. The value of J-B statistic is 7423.31, and the P-value is 0, which implies that the assumption that the daily yield series obeys a normal distribution is rejected at 1% confidence level, i.e., the daily yield series of CSI 300 stock index futures is not normally distributed.

Table 1. Descriptive Statistics of Futures Prices and Daily Returns

Statistics	Futures Price	Futures Daily Return Rate
Mean	3488.71	-0.00024
Median	`3466.8	-0.02
Maximum	5787.2	9.74
Minimum	2055.4	-10.64
Std.Dev.	828.53	1.54
Skewness	0.28	-0.39
Kurtosis	2.41	10.27
Jarque-Bera	91.21	7423.31
Probability	0	0

3.3. Statistical Test of CSI 300 Stock Index Futures Daily Returns

The article has been fully analyzed from the characteristics of daily returns of CSI 300 stock index futures, but in order to further determine whether its daily return series is smooth or not, a unit root test is still needed. The article carries out the ADF test on the yield data to make a smooth judgment by whether there is a unit root in its series. According to the unit root test results in Table 2, it can be found that the T-statistic in the ADF test results of the yield is -43.26 and the P-value is 0, which indicates that the yield series rejects the original hypothesis at the confidence level of 99%, and at this time, it can be considered that the yield data does not have a unit root and the series is smooth. Therefore, it can be concluded that the yield series of CSI 300 stock index futures is a smooth time series at 1% confidence level. In addition, the yield series of CSI 300 stock index futures passes the autocorrelation test and there is no autocorrelation between its yield series.

Table 2. Unit Root Test Results for Futures Daily Returns

ADF Inspection		**T-value**		
Statistics	**P-value**	**1% level**	**5% level**	**10% level**
-43.26	0.00	-3.43	-2.86	-2.57

4. Volatility characterization based on GARCH models

4.1. ARCH effect test of CSI 300 stock index futures

An initial regression model is established for price returns to obtain the benchmark regression results for daily returns as shown in Figure 2, and then the benchmark regression results are tested for ARCH effects.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
RETURN(-1)	-0.003092	0.017281	-0.178919	0.8580

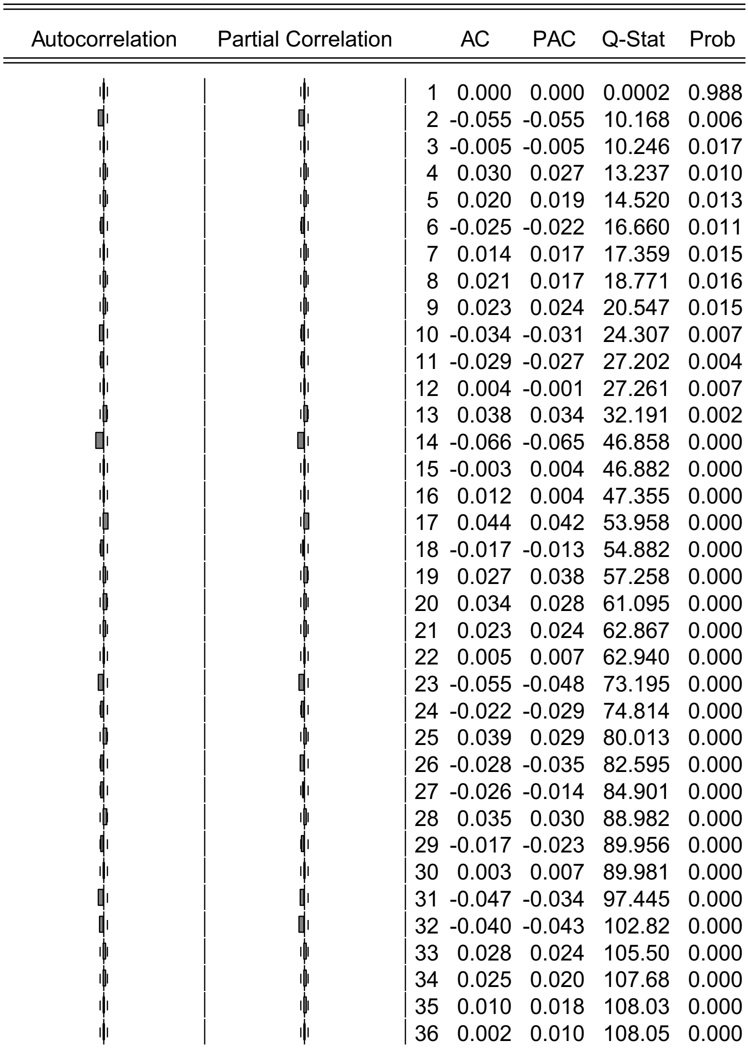
R-squared	0.000008	Mean dependent var	0.001740
Adjusted R-squared	0.000008	S.D. dependent var	1.540945
S.E. of regression	1.540938	Akaike info criterion	3.702960
Sum squared resid	7909.428	Schwarz criterion	3.704794
Log likelihood	-6168.131	Hannan-Quinn criter.	3.703616
Durbin-Watson stat	1.999170		

Figure 2. Screenshot of Benchmark Model Estimation Results for Futures Price Yields

The results of the ARCH effect test of CSI 300 stock index futures are shown in Table 3. The concomitant probability P=0 corresponding to the observed value R^2 indicates that there is an ARCH effect in the residual series of CSI 300 stock index futures at the confidence level of 5%, and a GARCH model can be established to further analyze the conditional heteroskedasticity of the residual series.

Table 3. ARCH Effect Test for the Residual Sequence of Futures Price Returns

F-statistic	Obs*R-squared	Prob. F(1,3329)	Prob. Chi-Square(1)
307.0795	281.3145	0	0



Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob
		1	0.000	0.000	0.0002	0.988
		2	-0.055	-0.055	10.168	0.006
		3	-0.005	-0.005	10.246	0.017
		4	0.030	0.027	13.237	0.010
		5	0.020	0.019	14.520	0.013
		6	-0.025	-0.022	16.660	0.011
		7	0.014	0.017	17.359	0.015
		8	0.021	0.017	18.771	0.016
		9	0.023	0.024	20.547	0.015
		10	-0.034	-0.031	24.307	0.007
		11	-0.029	-0.027	27.202	0.004
		12	0.004	-0.001	27.261	0.007
		13	0.038	0.034	32.191	0.002
		14	-0.066	-0.065	46.858	0.000
		15	-0.003	0.004	46.882	0.000
		16	0.012	0.004	47.355	0.000
		17	0.044	0.042	53.958	0.000
		18	-0.017	-0.013	54.882	0.000
		19	0.027	0.038	57.258	0.000
		20	0.034	0.028	61.095	0.000
		21	0.023	0.024	62.867	0.000
		22	0.005	0.007	62.940	0.000
		23	-0.055	-0.048	73.195	0.000
		24	-0.022	-0.029	74.814	0.000
		25	0.039	0.029	80.013	0.000
		26	-0.028	-0.035	82.595	0.000
		27	-0.026	-0.014	84.901	0.000
		28	0.035	0.030	88.982	0.000
		29	-0.017	-0.023	89.956	0.000
		30	0.003	0.007	89.981	0.000
		31	-0.047	-0.034	97.445	0.000
		32	-0.040	-0.043	102.82	0.000
		33	0.028	0.024	105.50	0.000
		34	0.025	0.020	107.68	0.000
		35	0.010	0.018	108.03	0.000
		36	0.002	0.010	108.05	0.000

Figure 3. Screenshot of Autocorrelation Analysis Results

According to Figure 3, the autocorrelation coefficient is 0.000 at lag 1 and then fluctuates positively and negatively with mostly small absolute values. The partial autocorrelation coefficient is 0.000 at lag 1 and fluctuates positively and negatively thereafter. And most of the PAC and AC values of the residual series of daily returns of CSI 300 stock index futures are within the interval of plus or minus two times of the estimated standard deviation. At lag 1, the P-value is 0.988, and the Q-statistic is not significant at significant levels at 1%, 5% and 10% confidence levels, at which time the Q-statistic test cannot reject the original hypothesis that there is no serial autocorrelation in the yield residual series. However, when the lagged period of return is 2 and more than 2 periods, the P value of Q statistic is less than 0.05, and the original hypothesis is rejected at 5% significance level, which means that there is serial autocorrelation in the residual series of daily return of CSI 300 stock index futures in lagged period of more than 1 period, and at this time, the regression results of the benchmark regression equation are no longer valid and credible, and it is necessary to revise the residual series of benchmark regression that has serial correlation. It is necessary to correct the residual series of the benchmark regression with serial correlation. The absolute values of PAC and AC in the corresponding lag 2 are 0.055, which are greater than 0.05, the absolute values of PAC and AC in the lag 3 are 0.005, which are less than 0.005, and the absolute values of PAC and AC in the lag 3 are close to 0. Therefore, it is considered that there is a second-order autocorrelation in the residual series of the daily returns of CSI 300 stock index futures.

4.2. Parameter Estimation of GARCH Model for CSI 300 Stock Index Futures

There are four commonly used GARCH models, GARCH(1,1), GARCH(1,2), GARCH(2,1), GARCH(2,2), so the fitting effects of the four different GARCH models need to be examined to determine the best-fitting GARCH model as the regression model that ultimately explains the volatility characteristics of the returns of CSI 300 stock index futures. In order to select an appropriate GARCH model, we need to consider the model's goodness of fit, the information criterion, and the model's predictive ability to ensure the model's reasonableness and applicability. AIC (Akaike Information Criterion) and SC (Schwarz Information Criterion) are two commonly used model selection criteria for evaluating the goodness-of-fit and the complexity of a statistical model. The smaller values of the AIC and SC criteria usually imply that the model is better. The smaller values of AIC and SC usually imply a better model. HQC (Hannan-Quinn Criterion) is another model selection criterion, the smaller the value of HQC, the better the model. Therefore, the article establishes four GARCH models for CSI 300 stock index futures and compares the significance of the coefficients of the four models, and selects the appropriate model according to the principle of AIC, SC and HQC minimization.

Table 4. Comparison of GARCH Model Fitting Effects for Daily Returns

Variable	Coefficient	Std. Error	Prob.	AIC	SC	HQC
GARCH(1,1)	0.03168	0.01796	0.07770	3.41242	3.41976	3.41504
GARCH(1,2)	0.02992	0.01802	0.09680	3.41219	3.42136	3.41547
GARCH(2,1)	0.02885	0.01766	0.10240	3.41172	3.42090	3.41501
GARCH(2,2)	0.02832	0.01776	0.11080	3.41202	3.42303	3.41596

The regression analysis of the daily return series was performed with four models, GARCH(1,1), GARCH(1,2), GARCH(2,1), and GARCH(2,2). In general, when selecting models, preference is given to models with smaller AIC values and SC and HQC values, because smaller values indicate a better model fit while controlling for model complexity. Table 4 shows that among these four models, the SC value of GARCH(1,1) is the smallest among the four models, and the AIC and HQC values of GARCH(2,1) are the smallest among the four models, but the P-value of the regression coefficient of the mean equation of GARCH(2,1) is 0.1024, which is not significant at 10% confidence level, and the GARCH(1,1)'s p-value of the regression coefficient for the mean equation is 0.0777, which is significant at the 10% confidence level. Therefore, overall, the GARCH (1,1) model has a better regression.

Table 5. Regression Results of the GARCH Model Variance Equation for Daily Returns

GARCH Model	Variable	Coefficient	Std. Error	z-Statistic	Prob.
GARCH(1,1)	C	0.030	0.004	6.700	0.000
	RESID(-1)^2	0.081	0.004	19.488	0.000
	GARCH(-1)	0.909	0.004	206.641	0.000
GARCH(1,2)	C	0.036	0.006	6.439	0.000
	RESID(-1)^2	0.099	0.006	15.996	0.000
	GARCH(-1)	0.617	0.094	6.550	0.000
	GARCH(-2)	0.271	0.090	3.013	0.003
GARCH(2,1)	C	0.025	0.004	5.986	0.000
	RESID(-1)^2	0.113	0.008	14.616	0.000
	RESID(-2)^2	-0.041	0.010	-4.331	0.000
	GARCH(-1)	0.920	0.006	157.512	0.000
GARCH(2,2)	C	0.016	0.006	2.534	0.011
	RESID(-1)^2	0.116	0.008	14.561	0.000
	RESID(-2)^2	-0.070	0.018	-3.789	0.000
	GARCH(-1)	1.214	0.218	5.573	0.000
	GARCH(-2)	-0.267	0.199	-1.342	0.180

Comparing the regression coefficients and P-values of the variance equations of the four models GARCH(1,1), GARCH(1,2), GARCH(2,1), GARCH(2,2), the results are shown in Table 5, and there are insignificant coefficients in the variance equation of the GARCH(2,2) model only. Combined with the conclusions of the analysis of the mean equation and the indicators of AIC, SC and HQC above, GARCH(1,1) is the better-fitting model, therefore, GARCH(1,1) should be chosen for the volatility analysis of CSI 300 stock index futures. The regression results of the GARCH(1,1) model for the daily returns of CSI 300 stock index futures are:

$$\mathrm{RETURN_t} = 0.03168 \times \mathrm{RETURN_{t-3}} \tag{3}$$

$$\sigma_t^2 = 0.03 + 0.081u_{t-1}^2 + 0.909\sigma_{t-1}^2 \tag{4}$$

Among them, the regression coefficients of the GARCH(1,1) model have p-values less than 0.01, which are significant at 1% confidence level. In the variance equation, the regression coefficient of RESID(-1)^2 is 0.081, which is greater than 0, implying that the shocks from outside the market will make the price volatility of the CSI 300 stock index futures market more intense. The regression coefficient of GARCH(-1) is 0.909, which indicates that the fluctuations of the daily return series of CSI 300 stock index futures will be significantly and positively affected by the fluctuations of the previous period. positive influence. In addition, the sum of the regression coefficient of RESID(-1)^2, 0.081, and the regression coefficient of GARCH(-1), 0.909, is 0.99, which is less than 1 but very close to 1, implying that the volatility of the daily yield series of the CSI 300 stock index futures has a high degree of persistence, and it is possible that the high degree of persistence in the volatility of this yield series can be attributed to the state transformation of the volatility .

Table 6. ARCH-LM Test Results for the GARCH(1,1) Model

F-statistic	Obs*R-squared	Prob. F(1,3329)	Prob. Chi-Square(1)
2.853979	2.853247	0.0912	0.0912

Finally, the ARCH-LM test is performed on the residual series of the constructed GARCH(1,1) model to test whether the GARCH model constructed for CSI 300 stock index futures is effective in eliminating the conditional heteroskedasticity of the benchmark regression model. Table 6 demonstrates the results of the ARCH-LM test. The p-value of the lagged 1st order statistic of the residual series of the GARCH(1,1) model constructed for CSI 300 stock index futures returns is 0.0912, which is greater than 0.05, indicating that there is no ARCH effect in the residuals of the constructed GARCH(1,1) model.

5. Conclusions and recommendations

5.1. Conclusions

The daily returns of CSI 300 stock index futures are not normally distributed, characterized by obvious left-skewed and spiked distributions, with autocorrelation of order 3 or higher and ARCH effects. The price fluctuations of China's CSI 300 stock index futures are positively affected by the fluctuations of the previous period, and the fluctuations show a certain degree of aggregation. For CSI 300 stock index futures, its own fluctuations have less impact on its price than shocks from outside the futures market, which will make the price fluctuations of CSI 300 stock index futures more intense, and these fluctuations have a high degree of persistence, and once the impact is produced, it will take a long time to return to the equilibrium state.

5.2. Recommendations

First, the left-skewed and spiked distributions of daily returns on CSI 300 index futures remind investors that the actual market risk is higher than under the assumption of a normal distribution. Left skewness implies a higher probability of extreme negative returns, while spikes indicate more frequent large swings. Therefore, investors need to take into account this non-normal distribution characteristic when setting stop-loss points and set aside a wider margin of safety to cater for the possibility of a sharp downturn.

In addition, due to the ARCH effect and volatility aggregation, investors need to recognize that market volatility is not randomly and evenly distributed. During periods of high market volatility, subsequent volatility is also more likely to remain high. Investors can employ dynamic risk management strategies. For example, when it is observed that CSI 300 index futures price volatility has begun to aggregate and increase in magnitude recently, investors with long positions may consider partially hedging their risk by selling a certain number of futures contracts to minimize possible losses.

Finally, considering the conclusion that price fluctuations are positively influenced by the previous period's fluctuations suggests that there may be some continuity in the market trend. If the previous period of market volatility was large and upward, then investors may consider following the trend and increasing their long positions appropriately. But at the same time, it should also be noted that the continuity of such volatility may lead to market overreaction, so it is necessary to combine with market fundamentals and other factors to determine whether the trend is reasonable. For example, when the macroeconomic data does not support a sustained rise in the stock market, but the price of CSI 300 stock index futures continues to rise due to the inertia of the previous upward fluctuations, investors need to operate with caution and avoid blindly following the trend.

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Effectiveness Test of Trend Following Strategy for Emerging Assets and Traditional Assets: A Case Study of Digital Currency and Index Futures

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Abstract. The cryptocurrency market has similar characteristics to the futures market, and trend-following strategies are attractive in this market. This paper uses the spot price data of Bitcoin against the US dollar from January 1, 2013 to September 27, 2023, as well as the daily data of the S & P 500 index and the Shanghai and Shenzhen 300 index in the same period. A trend-following strategy is used to evaluate indicators such as return, Sharpe ratio, Sortino ratio, risk exposure and maximum drawback by optimizing parameters. By analyzing ten years of data on Bitcoin, the research revealed the potential return on investment of the cryptocurrency trend-following strategy, which achieved an annualized return of 112.7%. The results show that the trend tracking strategy of digital currency is more significant under the special conditions of increasing market volatility. Bitcoin shows potential value in investment portfolios, especially when market volatility increases and may become a hedging tool and provide more diversified investment strategies.

Keywords. Trend tracking; digital currency; stock index futures; quantitative investment

1. Introduction

Trend-following strategy is a method of using market trends to invest, through the analysis of asset price changes, tracking the direction of the trend, and flexible adjustment of positions to obtain long-term profits. This strategy emphasizes dynamic management,

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using technical analysis tools and risk control mechanisms to maximize gains when the trend continues, while reducing losses when the trend reverses[1].

This paper focuses on testing the effectiveness of trend-following strategies for emerging assets and traditional assets. The purpose of this research is the comparison between Bitcoin as a representative of digital currency and traditional index futures (S & P 500 index and CSI 300 index). Bitcoin [2][3] was introduced in 2009 as a digital currency and fiat currency (e.g. USD, GBP, JPY) with the characteristics of fast settlement, diversification and inflation hedging [4], and it is similar to a commodity in this sense. In fact, the US Commodity Futures Trading Commission classifies Bitcoin as a commodity [5]. Bitcoin shares many similarities with gold, both of which are considered to have speculative safe-haven asset properties [6], and their decentralized nature protects them from financial variables such as inflation and politics, suggesting that Bitcoin has an effective hedging and diversification interest in global indices [7]. However, unlike gold, Bitcoin has consistently larger returns and volatility, and therefore a greater risk of price volatility. By 2020, the total assets of global crypto hedge funds had reached $3.8 billion, almost doubling from $2 billion in 2019. The proportion of funds with assets under management exceeding US $2,000 reached 46%, a significant increase from 35% in 2019. Among the funds surveyed, the average AUM reached 4,280 $100 billion, up $300 billion from 2019. [8] One of the most common strategies is quantitative, and trend-following funds have a huge opportunity potential in the Bitcoin market, with an estimated maximum AUM capacity of 3.2.3 billion US dollars, showing huge potential for growth[9].

In this paper, First, we evaluate metrics such as return, Sharpe ratio, Sortino ratio, exposure, and maximum drawback by implementing trend tracking and optimizing parameters to determine their match in the digital asset market. With the help of Sharpe and Sortino ratios, we measure the attractiveness of risk-adjusted returns and, after assessing correlations, examine the applicability of BTCUSD as a hedge against the S & P 500 and CSI300. Then, we study the index and double index moving average strategies, identify the relevant characteristics, and compare the performance with the traditional strategies and the S & P 500 and CSI300. The results of this paper show that: first, the Bitcoin trend-following strategy performs more significantly than the traditional financial index under special market conditions (such as during the COVID-19 epidemic); second, the DEMA trend-following strategy of Bitcoin is relatively stable in terms of Sharpe ratio, especially in the bear market; Third, there is a trend of negative or no correlation between Bitcoin and traditional financial indexes, indicating that Bitcoin may serve as an effective hedging tool[10].

This paper argues that digital currency may become a hedging tool and provide more diversified investment strategies. In the past ten years, there has been a trend of negative or no correlation between BTCUSD and the S & P 500 Index and the CSI 300 Index. This indicates that BTCUSD may become an effective time hedging tool for trend tracking of S & P 500 index and Shanghai and Shenzhen 300 index in a period of time, providing investors with more diversified investment strategies.

2. Data description and method introduction

2.1 Data description

We use the spot price data of Bitcoin against USD from January 1, 2013 to September 27, 2023, which comes from the CoinMarketCap trading platform. At the same time, we also collected the daily data of Bitcoin in the same period, the daily data of S & P 500 index from Flush Finance, and the data of CSI 300 index from JionQuant. With a total of 3922 lines in our sample in this data set, the data is relatively complete, although in some cases there are partial missing values.

To ensure the completeness of the data, we adopt a padding strategy to deal with these missing values. Specifically, we choose a method to fill in the missing values with the average value of 10 days before and after. The choice of this filling method does not affect the results of the experiment, as we focus on recent data. This data filling method not only helps to maintain the integrity of the time series, but also reduces the impact of missing data to a certain extent. Therefore, we believe that the data processing method used ensures that we can obtain reliable analytical conclusions in our study.

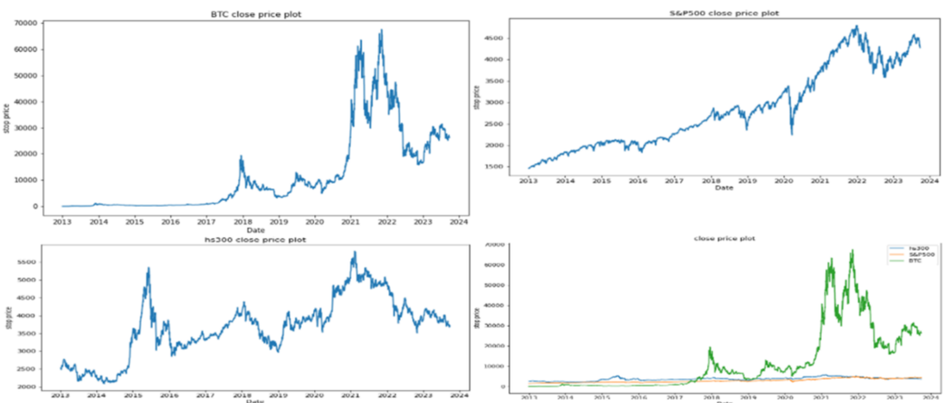


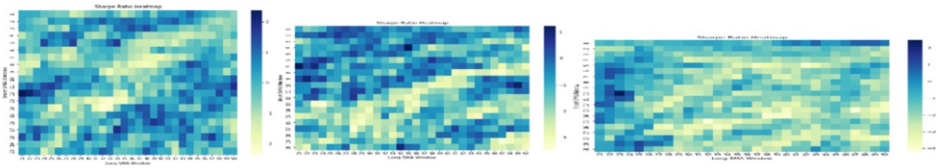
Fig. 1. Closing prices between January 1, 2013 and September 27, 2023

We use trend-following strategies, including simple moving average, exponential moving average, and double exponential moving average. For the long and short windows of BTCUSD (Bitcoin Exchange Dollar), S & P 500 Index and Shanghai and Shenzhen 300 Index, we have chosen a short period of 1 to 20 days and a long period of 21 to 50 days. When the rolling average of the short period window is above the long period window, the strategy generates a "buy" signal; conversely, when the rolling average of the short period window is below the long period window, the strategy generates a "sell" signal.

These strategies were backtested with an initial capital of $10,000, and each "buy" or "sell" signal executed the maximum volume of the corresponding asset. We maximize the Sharpe ratio by carefully optimizing the size of the short and long cycles, focusing on key indicators such as the number of transactions, the winning rate, and the rate of return. Our study takes into account a number of factors, including the assumption that transaction costs, bid-ask spreads, slippage, and the impact of trading on the market are negligible. A comprehensive analysis of these factors helps ensure that our assessment of policy performance is more comprehensive and reliable.

2.2 Trend-following model

Traditional trend estimation techniques, including Simple Moving Average (SMA), Exponential Moving Average (EMA), and Double Exponential Moving Average (DEMA), are employed. We give a brief summary of these methods. For a simple average of short and long rolling windows of fixed size.



(a) BTCUSD spot Sharpe ratio (b) S&P 500 futures Sharpe ratio (c) HSI 300 futures Sharpe ratio

Fig. 2. Trend of risk-adjusted SMA returns from 2013 to 2023 (Sharpe ratio)

We use three trend following indicators to perform our analysis, which are Simple Moving Average, Exponential Moving Average, and Double Exponential Moving Average.

3. Results

Through the study of Figure 3-1, we observe that in the data slices from 2013 to 2019, the performance of BTCUSD trend tracking strategy (long period is 20 days, short period is 5 days) is not raw eye visible relative to the traditional financial index. However, in the data sample from 2020 to 2023, especially during the period from the beginning to the end of the COVID-19 outbreak, global financial markets have been greatly impacted. In this unusual market environment, it is difficult for investors to gain considerable profits in traditional financial indexes. It is worth noting that during the COVID-19 outbreak, the DEMA strategy in the BTCUSD trend-following strategy has been relatively stable in terms of Sharpe ratio. In contrast, this strategy is stronger than the traditional financial index in a strong bear market, which also provides investors with the opportunity to seek more robust investment options when the market is turbulent.

Therefore, our results suggest that the DEMA strategy in the BTCUSD trend-following strategy may be a powerful tool for investors to seek relatively stable returns in a strong bear market under special market conditions, especially when the global financial market is subject to major shocks. This finding provides investors with more investment options in the face of uncertainty and increased market volatility.

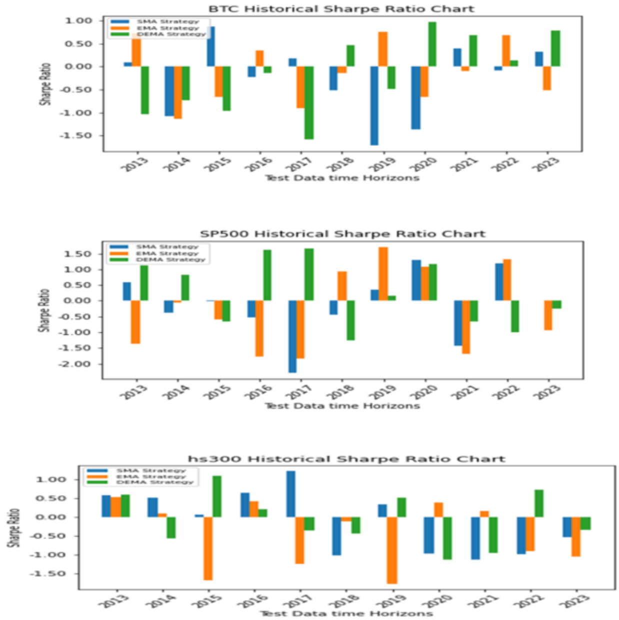


Fig. 3. -1 Historical data of Bitcoin, S & P 500 and CSI 300 Index, and the benchmark Sharpe ratio histogram of each strategy (SMA, EMA, DEMA) over the years.

Table 1. -1 Performance of three types of trend tracking strategies of BTC

	BTC daily line SMA	BTC daily EMA	BTC daily line DEMA
Start and end time of back test	**2013/01/01-2023/09/27**	**2013/01/01-2023/09/27**	**2013/01/01-2023/09/27**
Number of test days	**3922**	**3922**	**3922**
Number of transactions	**187**	**80**	**361**
Sharpe ratio	**2.380**	**1.12**	**1.71**
Principal	**10000**	**10000**	**10000**
Earnings	**122725**	**28333**	**100220**
Rate of return	**1127.3%**	**183.3%**	**902.2%**
Average annual rate of return	**112.7%**	**18.3%**	**90.2%**
Winning rate	**57.2%**	**57.5%**	**50.1%**
Service charge	**0**	**0**	**0**

Table 2. -2 Performance of Three Trend Tracking Strategies of US S & P 500 Index

	S & P 500 Daily SMA	S & P 500 daily EMA	S & P 500 Daily DEMA
Start and end time of back test	**2013/01/01-2023/09/27**	**2013/01/01-2023/09/27**	**2013/01/01-2023/09/27**
Number of test days	**2690**	**2690**	**2690**
Number of transactions	**124**	**112**	**166**
Sharpe ratio	**1.24**	**0.58**	**1.12**
Principal	**10000**	**10000**	**10000**
Earnings	**16277**	**13866**	**16008**
Rate of return	**62.8%**	**38.7%**	**60.1%**
Average annual rate of return	**6.3%**	**3.9%**	**6.0%**
Winning rate	**53.2%**	**53.6%**	**53.0%**
Service charge	**0**	**0**	**0**

Table 3. -3 Performance of Three Trend Tracking Strategies of China CSI 300 Index

	Shanghai and Shenzhen 300 day line SMA	Shanghai and Shenzhen 300 day line EMA	Shanghai and Shenzhen 300 day line DEMA
Start and end time of back test	**2013/01/01-2023/09/27**	**2013/01/01-2023/09/27**	**2013/01/01-2023/09/27**
Number of test days	**2611**	**2611**	**2611**
Number of transactions	**115**	**107**	**141**
Sharpe ratio	**2.46**	**1.10**	**1.18**
Principal	**10000**	**10000**	**10000**
Earnings	**19974**	**14957**	**15352**
Rate of return	**99.7%**	**49.6%**	**53.5%**
Average annual rate of return	**10.0%**	**5.0%**	**5.4%**
Winning rate	**60.5%**	**55.7%**	**60.4%**
Service charge	**0**	**0**	**0**

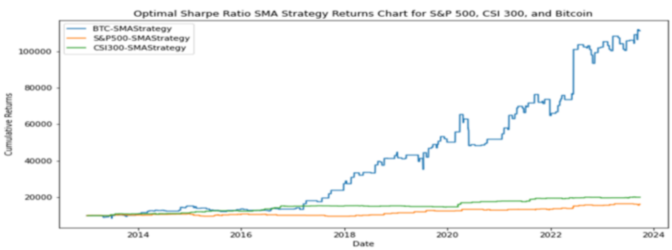


Fig. 4. -2 Comparison of Trading Performance of Historical Data Strategy SMA of Bitcoin, S & P 500 and CSI 300 Index

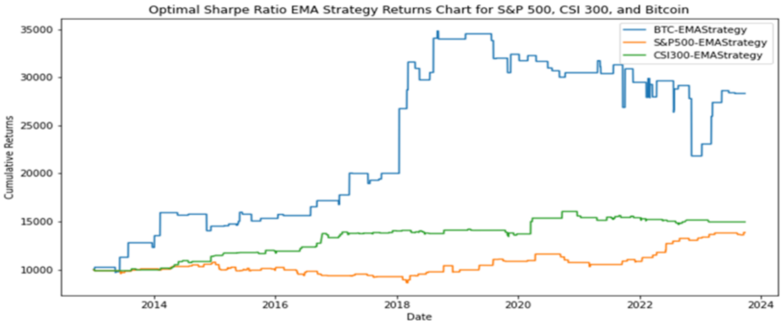


Fig. 5. -3 Comparison of historical data strategy EMA trading performance of Bitcoin, S & P 500 and CSI 300 index

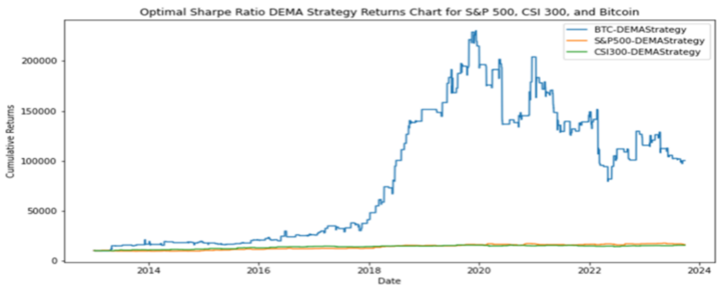


Fig. 6. -4 Comparison of Trading Performance of Bitcoin, S & P 500 and CSI 300 Index Historical Data Strategy DEMA Strategy

Through in-depth study of Table 3-1, Table 3-2 and Table 3-3, we find that under the optimal parameter setting, the total return of the S & P 500 index between 2013 and 2023 is only 62.8%, and the average annual return is 6.28% compared to a total return of 99.7% for the CSI 300. However, compared to traditional metrics, BTCUSD has returned an impressive 1127.3% over the same period, or about 112.7% annually.

Further study of the results of Figures 3-2, 3-3, and 3-4 shows that the three trend-following strategies perform significantly better than traditional financial indicators on BTCUSD. This result not only highlights the effectiveness of trend following strategies in the digital asset market, but also emphasizes the potential value of digital assets in the portfolio.

It is worth noting that in the past decade, we have seen a trend of negative or no correlation between BTCUSD and the S & P 500 Index and the CSI 300 Index, which suggests that BTCUSD may become an effective time hedge for the S & P 500 index and trend tracking for some time, thus providing investors with a more diversified investment strategy.

In the past decade, we have observed a trend of negative or no correlation among BTCUSD, S & P 500 Index and CSI 300 Index for quite a long time. This trend suggests that BTCUSD may become an effective time hedging tool for trend tracking of the S & P 500 and CSI 300.This negative correlation or no correlation suggests that BTCUSD shows a different direction of movement from the traditional stock market in a certain period, thus providing investors with a promising way to diversify their portfolios. This further emphasizes the potential role of digital assets in asset allocation, making them an effective hedge against stock market volatility.

A small negative correlation between the BTCUSD spot price and stock returns can be observed throughout our data set, although it is not statistically significant.

From the analysis of Figures 3 – 5, we observe that the optimal long-period window is typically larger than 23 days. In addition, the SMA values of the long period and the short period are positively correlated, and the correlation exceeds 0.65. In contrast, the optimal long and short period windows of EMA and DEMA do not show a significant correlation.

However, due to the young nature of the Bitcoin market, the sample size of the rolling window is relatively small. Therefore, as the Bitcoin market matures, it is necessary to retest this assertion to ensure its continued validity at different stages of market development. From Tables 3-1, 3-2, and 3-3, we have observed that the trend-following strategy has shown a trend toward sustained profitability, regardless of the averaging strategy. It is important to note that the highest achievable risk-adjusted returns are similar to those in commodity markets.

4. Conclusion

Compared with the traditional financial index, the trend tracking strategy of digital currency is more significant under the special conditions of increasing market volatility. In the data sample from 2013 to 2019, when the long period of BTCUSD trend tracking strategy is 20 days and the short period is 5 days, it does not show advantages in the traditional financial index. However, in the data from 2020 to 2023, especially in the period from the beginning to the end of the COVID-19 outbreak, the global financial market has suffered a great impact. In this abnormal market environment, the traditional financial index is difficult to bring considerable returns to investors, while the DEMA strategy in BTCUSD trend tracking strategy is relatively stable and stronger in Sharpe ratio.

The DEMA strategy showed relatively stable characteristics during the COVID-19 epidemic. In the case of severe shocks to global financial markets, the performance of DEMA strategy in BTCUSD trend-following strategy is stronger than that of traditional financial index, providing investors with the opportunity to seek relatively stable returns in a strong bear market.

Digital currencies show potential value in portfolios. Through the in-depth study of Table 3-1, Table 3-2 and Table 3-3, we find that under the optimal parameter setting, BTCUSD has achieved a staggering 1127.3% return between 2013 and 2023, with an average annual return of about 112.7%. By comparison, the S & P 500 has a total return of just 62.8%, or an average annual return of 6.5%.The total yield of the CSI 300 Index is 99.7%, with an average annual return of about 10%. This underscores the potential value of digital currencies in portfolios, especially at a time of increased market volatility.

To sum up, our results provide investors with more investment options in the face of uncertainty and increased market volatility, especially in special market conditions, the DEMA strategy in the digital currency trend tracking strategy may become a powerful tool for investors to seek relatively stable returns in a strong bear market. This finding provides an important reference for investors to make decisions, and also provides a basis for further study of the role of digital assets in the portfolio.

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A Simulation About Digital Economy, Circulation Efficiency and High-Quality Economic Development of the Greater BayArea

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Abstract: This study applies a system dynamics model using 2014–2023 data to examine how digital infrastructure, R&D investment, and software talent affect resource allocation and circulation efficiency in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA). The findings reveal that digitalization notably enhances economic quality by boosting circulation efficiency. It is recommended that cross-regional data networks and talent mobility be strengthened to support coordinated regional development.

Keywords: Digital Economy, Circulation Efficiency, System Dynamics, High-Quality Development

1. Introduction

In the era of rapid globalization and informatization, the digital economy has emerged as a core driver of high-quality economic development at both global and regional levels [1]. It transforms production modes, business models, and industrial structures through digital technology innovations. Circulation efficiency—key to reducing transaction costs, optimizing resource allocation, and enhancing market competitiveness—has been significantly boosted by next-generation information technologies that improve logistics, inventory management, and supply chain optimization, thereby reshaping circulation modes [2]. However, its development entails complex system dynamics, involving feedback among technological innovation, policy regulation, market structure, and talent cultivation. This paper employs a system dynamics simulation to model the interaction between the digital economy and circulation efficiency [3].

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2 Literature review and theoretical basis

2.1 Literature Review

Existing literature has thoroughly examined the digital economy's role in boosting circulation efficiency, high-quality development, and coordinated regional economic development [4]. Specifically:

(1) Digital economy, industrial innovation, and high-quality development

It enhances circulation efficiency and drives the digital transformation of circulation industries, despite regional differences. It indirectly fosters urban industrial innovation through circulation modernization—with virtual clustering acting as a bridge—and positively influences technological innovation in circulation enterprises, especially in non-state-owned and western regions [5-7]. Moreover, it promotes innovation efficiency, consumption expansion, industrial structure upgrading, and green total factor productivity [8-9].

(2) Digital economy, green development of the circulation industry, and coordinated regional economic development

By improving green technology innovation, the digital economy indirectly reduces industry carbon emissions and significantly drives high-quality development in the circulation industry, particularly via digital industrialization. Research shows that coordinating the digital economy with sectors like green finance, rural revitalization, and rural logistics is crucial for balanced regional development [10-12]. Its impact on urban environmental quality, logistics efficiency, and economic resilience exhibits marked spatial heterogeneity, underscoring the importance of spatial effects and policy influences in shaping regional development strategies [13].

Comprehensive Review of Literature

There are potential shortcomings in previous studies:

① Complexity of systemic dynamic relationships

Although prior research highlights the digital economy's positive effects on circulation efficiency and industrial innovation, it often overlooks the complex dynamic feedback among these factors by relying on static or cross-sectional analyses.

②Multi-dimensional analysis of regional economic coordination

Studies typically focus on specific regions or sectors, lacking a deep examination of unique economic entities like the GBA. In contrast, system dynamics models can integrate policy, market, and social factors to simulate the synergistic development of the digital economy and logistics efficiency in the GBA.

In summary, there are still shortcomings in the in-depth analysis of system dynamic relationships, multi-dimensional consideration of regional economic coordination development, and evaluation of the long-term effects of policy impacts. By applying SD models, a more comprehensive simulation and analysis of these complex relationships can be conducted, providing more precise policy recommendations for optimizing digital economy and logistics efficiency in the GBA.

2.2 System Element Analysis and Theoretical Framework Construction

2.2.1 System Element Analysis

The digital economy subsystem enhances information flow by upgrading digital infrastructure and broadening the application of digital technologies . Continuous R&D investment further drives its development, propelling digital transformation and boosting regional competitiveness and innovation. This subsystem interacts with those of circulation efficiency and high-quality economic development, collectively shaping overall system dynamics. The circulation efficiency subsystem improves logistics via optimized infrastructure investment and enhanced human resources, reducing transaction costs and shortening supply chain cycles. Meanwhile, the high-quality economic development subsystem aims for sustainable growth by promoting both the digital economy and improved circulation efficiency.

2.2.2 System Causal Feedback Path Analysis
Based on the above analysis, the causal feedback path of the system elements is represented by initial letters. The causal feedback path of the digital economy system is as follows.
Causal feedback path of the digital economy system:
Infrastructure investment (ii) → R&D expenditure (R&D) → Number of software information service personnel (SN) → Software business revenue (SR) → Digital innovation product revenue (Dr_DE)
Causal feedback path of the logistics and supply chain system:
Digital innovation product revenue (Dr_DE) → GDP → Fixed asset investment volume (IFA) → Policy support (PN) → Number of circulation industry personnel (NC) → Miles of roads and railways (RM) → Goods turnover volume (CT) → Digital innovation product revenue (Dr_LS)
Interaction feedback path between systems:
Digital innovation product revenue (Dr_LS) → Infrastructure investment (ii)

3. System dynamics model construction, variable selection and data source

3.1 Data Sources for Variables

Based on the above analysis, the following system dynamics model is established. Here I conduct simulation using Vensim PLE.
(I) Data Obtained from Reference Materials
GDP, investment in infrastructure, the number of people engaged in software information services, software business revenue, and revenue from digital innovative products are obtained from the Statistical Yearbook, while the added value of the logistics industry and the number of logistics industry employees, the length of highways and railways, and the volume of goods in transit are obtained from the China Logistics Yearbook. The number of policy support measures considers the lag in the effect of policies, and the policy data is obtained by Python scraping and downloading all notices, announcements, and policy documents issued by GBA governments from 2014 to 2023 to date. Then, the data is preprocessed, cleaned, and formatted, and necessary unit conversions are made to facilitate model calculations.
(2) Establish regression model
Since the revenue of digital innovation products cannot be directly obtained from statistical data, the regression analysis method is used to estimate the known statistical indicators, and the regression equation is as follows:
Digital economy system: Dr_DEt=2.5+0.8.SRt+0.5.R&Dt+0.2.SNt
Logistics and Supply Chain Systems: Dr_LSt=1.8+0.6.CTt+0.4.RMt+0.3.NCt

In order to place variables of different orders of magnitude in the same graph, a minimum-maximum normalization process is performed for each variable so that all variables have a value range between 0 and 1. As shown in Figure 1.

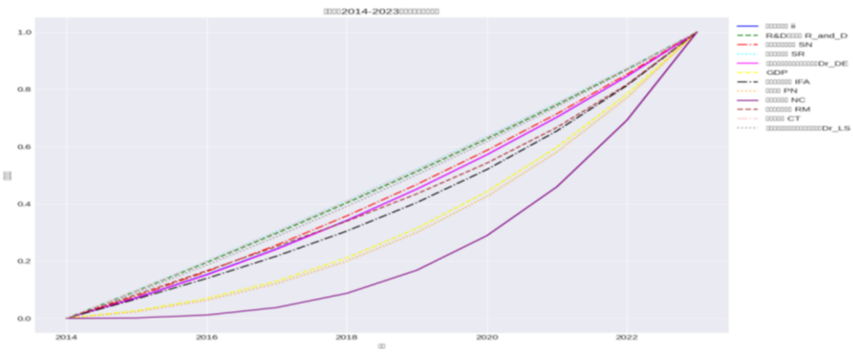

Figure 1 Simulation result

3.2 Analysis of Simulation Results

3.2.1 Overall Trend Analysis

By analyzing the changing trends of the normalized variables, the following trends can be observed from Figure 1.

(1) The rapid development of the digital economy has driven the prosperity of scientific and technological talents and the software industry. This series of chain reactions reflects the crucial role of infrastructure and R&D investment in the development of the digital economy, as well as the positive interaction between talents and industries.

(2) The digital economy has played an important role in driving macroeconomic growth, further promoting the strengthening of investment and policy support. This reflects that the digital economy has not only developed rapidly on its own, but also promoted the improvement of the overall investment environment and policy environment by driving economic growth.

(3) Policy support and economic growth have promoted the improvement and efficiency of the logistics system, forming a strong support for the digital economy. Improved logistics efficiency and digitalization not only optimize supply chain management, but also further promote infrastructure investment through feedback mechanisms, forming a virtuous cycle.

3.2.2 Sensitivity analysis

In order to deeply understand the influence of key parameters and variables in the model on the system behavior, sensitivity analysis of the model helps to identify which parameters have a significant impact on the model output and find the key factors that play a role in economic development. Make a ±20% change for each parameter, the specific steps are as Figure 2 and Figure 3.

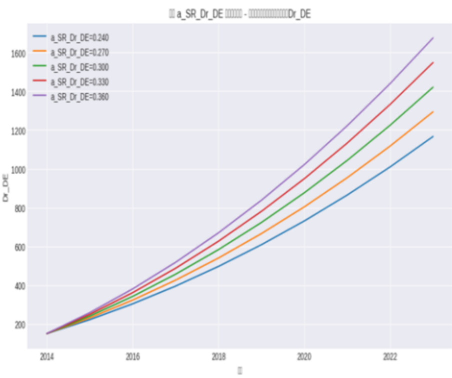

Figure 2 Sensitivity analysis

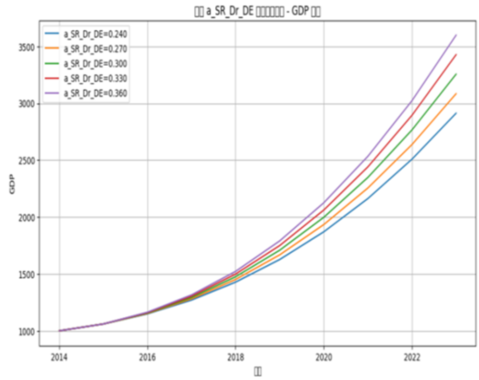

Figure 3 Sensitivity analysis of parameter a_2

Through the sensitivity analysis, the following conclusions are drawn:
① Importance of key parameters and robustness of the model: Parameter a1 has the greatest impact on the development of the digital economy, highlighting the key role of software business revenue in driving revenue growth of digital innovative products.
②Policy implications
Software revenue is the most sensitive to the impact of the digital economy, and increasing its impact coefficient can significantly accelerate the development of the digital economy. The driving effect of digital economy on GDP depends on its influence coefficient on GDP, and adjusting this parameter can simulate different degrees of economic dependence. The parameters in the logistics system have more direct influence on the logistics-related variables, and less indirect influence on the digital economy.

4. Conclusion and discussion

(1) Increase support for the digital economy: Due to the key impact of the digital economy on GDP growth, governments and enterprises should increase investment in the software industry and digital innovation, and promote the improvement of software business revenue and digital innovation products.
(2) Optimize the logistics system: improve the volume of goods and logistics efficiency, and have a direct role in promoting the digital innovation of the logistics supply chain. The policy should focus on strengthening the construction of logistics infrastructure and improving the level of logistics informatization.
(3) Sensitivity and key variables of the model:
Sensitivity analysis helps identify the parameters in the model that have the greatest impact on system behavior. By adjusting the key parameters, different scenarios can be simulated and the impact of each factor on the development of the system can be evaluated. This provides a quantitative basis for policy formulation and strategic planning.

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Can Overseas Background of Executives Improve Corporate Budget Slack?—Based on the Perspective of Risk-Taking and Environmental Volatility

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Abstract. Budget management is a cornerstone for achieving high-quality and modernized economic development in China. As a critical component of budget systems, budget slack is influenced by multiple factors, among which the intellectual capital formed by executives' overseas backgrounds has become a focal point for corporate discussion. This study uses data from A-share listed companies in Shanghai and Shenzhen from 2016 to 2022 to examine the impact of executives' overseas backgrounds on corporate budget slack from the perspective of risk-taking, further exploring the moderating role of environmental uncertainty in this relationship. The results show that executives' overseas backgrounds can inhibit corporate budget slack by enhancing the level of corporate risk-taking. Environmental uncertainty exhibits a complementary effect in the relationship between executives' overseas backgrounds and budget slack. Heterogeneity analysis reveals that the impact of executives' overseas backgrounds on budget slack is more pronounced in non-state-owned enterprises, small-scale enterprises, and enterprises with weaker external oversight.

Keywords. Executives’ overseas background; Budget slack; Risk-taking; Environmental volatility

1. Introduction

The 20th CPC National Congress highlighted improving the modern budget system to guide national development. Budget slack–suboptimal targets set by subordinates due to information asymmetry or self-interest–harms performance and sustainability. Upper Echelons Theory suggests executive traits influence decisions; studies link gender, age, and risk preferences to budget slack. Imprinting Theory indicates overseas experience shapes decision-making, yet its connection to budget slack remains unexplored, warranting further research.

Executives with overseas backgrounds, influenced by the culture and values of their study or work abroad, possess advanced governance knowledge and rich management experience. They can collide with local executives in terms of theoretical

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and practical insights, fostering mutual inspiration, breaking cognitive rigidities, and forming diverse management teams, thereby enhancing corporate governance (Gao, 2009)[1] and improving budget management systems. This assists China in achieving internationalized and modernized governance systems. Moreover, due to frequent global events such as the COVID-19 pandemic, the Russia-Ukraine conflict, and the Israel-Palestine conflict, the willingness of overseas personnel to return has surged, leading to a sharp increase in the number of returnees seeking employment. Against this backdrop, addressing whether executives' overseas backgrounds affect budget slack and its underlying mechanisms holds strategic significance for improving budget management systems and optimizing intellectual capital structures.

This study examines how executives' overseas backgrounds affect corporate budget slack using A-share listed firms in China. It explores the underlying mechanisms and contextual variations. Contributions include: (1) Expanding budget slack research by linking it to executives' overseas experience, enriching studies on its economic consequences and clarifying the mechanisms; (2) Identifying transmission pathways through external environment and internal risk-taking factors, enhancing the "overseas backgrounds-budget slack" framework. By revealing how and when these effects intensify or weaken, the study provides new insights and policy implications, offering incremental theoretical and practical value.

2. Research Mechanism and Hypotheses

(1) Executives' Overseas Backgrounds and Budget Slack

Budget slack arises from factors like budget formulation, fairness, information asymmetry, and individual behavior. This study examines how executives' overseas backgrounds influence budget slack through cultural convergence (Convergence Theory). Overseas experiences shape executives' values, fostering fairness, individualism, rule consciousness, and reputation awareness—key factors in budget slack dynamics. Compared to local executives, those with overseas backgrounds exhibit stronger fairness preferences, reducing opportunism and improving budget alignment[2]. They also enhance transparency and self-regulation, mitigating information asymmetry [3]. Reputation-driven behavior further encourages realistic budget assessments, curbing slack [4]. Imprinting Theory suggests overseas experiences instill long-term perspectives, reducing myopic budgeting [5]. Knowledge-Based and Resource-Based Theories highlight their unique risk assessment and technological skills, improving budget accuracy. Additionally, Upper Echelons Theory indicates these executives foster positive employee relations, reducing slack-inducing negativity [6].

Thus, overseas backgrounds correlate with lower budget slack by: Enhancing fairness and transparency—reducing opportunism and information gaps. Promoting reputation and long-term focus—aligning budgets with sustainable goals. Leveraging unique skills—improving risk assessment and resource allocation.

Hypothesis (H1): Executives' overseas backgrounds negatively correlate with budget slack.

(2) The Mediating Role of Risk-Taking

Contingency theory suggests budget slack acts as a risk buffer, with its intensity varying based on external and internal conditions [7]. Higher operational risks increase slack as a resource cushion, creating a substitution effect between slack and risk capacity. Reducing slack thus requires stronger risk-bearing ability.

Upper echelons theory highlights that overseas executives' distinct cognitive frameworks and values shape risk-related decisions [8]. Cross-cultural exposure fosters greater confidence, independent judgment, and risk tolerance [9]. Their expertise in risk prediction and mitigation enhances corporate risk management. Additionally, they cultivate error-tolerant cultures and peer effects, elevating overall risk-taking. Social capital theory underscores their global networks, which improve market insight, innovation, and sustainability—further boosting risk capacity .

Hypothesis (H2): Overseas executives reduce budget slack by strengthening corporate risk-taking.

3.Research Design

(1) Data Sources and Sample Selection

This study examines 2016 - 2020 A-share listed firms (excluding ST/*ST/PT/financial firms) to analyze budget slack evolution in China. Data combines manual collection from annual reports with CSMAR, CNRDS, and East Money databases, with variables winsorized at 1%/99% to reduce outliers.

(2) Variable Selection

① Dependent Variable

Budget Slack (Slack): This study calculates budget slack using the disclosed operating income in annual reports. The specific formula is:

$$Slack = \alpha_n + \alpha_n^*$$

Where α_n is the actual average growth rate of industry operating income in year n, and α_n* is the budgeted growth rate of operating income for a specific company in year n.

② Independent Variable

Executives' Overseas Background (Overseaback): Executives with overseas backgrounds are defined as board members or senior managers who have studied or worked in countries or regions outside China. The proportion of executives with overseas backgrounds in the company is used to measure this variable

③ Mediating Variable

Risk-Taking Level (Risk): Measured using the volatility of corporate earnings. the adjusted ROA is calculated by subtracting the industry average ROA from the company's ROA in the baseline year. The two-period rolling standard deviation of the industry-adjusted ROA is then used to measure corporate risk-taking. A higher value indicates a higher risk-taking level.

④ Moderating Variable

Environmental Uncertainty (EU): the coefficient of variation of operating income is used to measure environmental uncertainty.

(3) Model Design

① Baseline Regression Model

To test H1, the following baseline regression model is constructed:

$$Slack_{i,t} = \beta_0 + \beta_1 Oveseaback_{i,t} + \sum Controls + \sum Ind + \sum Year + \theta$$

Where i represents the enterprise, t represents the year; Slacki,t is the dependent variable, representing the budget slack of listed company i in year t; Oveseabacki,t is the core independent variable, representing the overseas background of executives in listed company i in year t; ∑Controls represents the selected control variables; ∑Ind and ∑Year represent industry and year fixed effects, respectively; θis the random disturbance term. If β1 is significantly negative, executives' overseas backgrounds are significantly negatively correlated with corporate budget slack; otherwise, they are positively correlated or unrelated.

② Mediation Effect Model

To test the mediating role of risk-taking, the following models are constructed:

$$Risk_{i,t} = \alpha_0 + \alpha_1 Oveseaback_{i,t} + \sum Control + \sum Ind + \sum Year + \theta$$

$$Slack_{i,t} = \omega_0 + \omega_1 Oveseaback_{i,t} + \omega_2 Risk_{i,t} + \sum Control + \sum Ind + \sum Year + \theta$$

Risk i,t represents the mediating variable—risk-taking. Other variables are defined as in Model (1). If the coefficients of risk-taking (Risk) in Models (2) and (3) are both significant, it indicates that executives' overseas backgrounds affect budget slack by influencing risk-taking. If the coefficient of executives' overseas backgrounds (Overseaback) ω_1 is insignificant, risk-taking plays a full mediating role; if ω_1 is significant, risk-taking plays a partial mediating role.

4. Empirical Analysis

(1) Correlation Analysis

The correlation coefficient between executives' overseas backgrounds and budget slack is -0.053, significant at the 1% level, preliminarily supporting Hypothesis H1. The correlation between risk-taking and budget slack is -0.056, significant at the 1% level, suggesting a negative relationship. Environmental uncertainty and budget slack have a coefficient of 0.068, significant at the 1% level, indicating that environmental uncertainty may exacerbate budget slack. The correlation between executives' overseas backgrounds and risk-taking is 0.078, significant at the 1% level, suggesting that overseas backgrounds may enhance risk-taking.

Table 1 Correlation Analysis

	Slack	Oveseaback	Risk	EU
Slack	1			
Oveseaback	-0.053***	1		
Risk	-0.056***	0.078***	1	
EU	0.068***	-0.016	-0.001	1

***, **, and * denote significance at 1%, 5%, and 10%, respectively.

All correlation coefficients are below 0.5, indicating no severe multicollinearity. Further variance inflation factor (VIF) tests confirm this (maximum VIF = 1.82 < 10).

(2) Baseline Regression

①Main Regression Results

Columns (1) and (2) of Table 2 present the main regression results, while columns (3) show the impact of risk-taking on budget slack.

Table 2 Baseline Regression

Variable Category	(1)	(2)	(3)
	Slack	Slack	Slack
Oveseaback	-0.434***	-0.382***	
Risk			-0.238**
Size	-0.021*	-0.024**	-0.025**
ListAge	0.038	0.044	0.037
Dual	0.005	0.012	-0.002
Indep	-0.313	-0.31	-0.279
Growth	0.627***	0.649***	0.626***
INV	0.137	0.069	0.11
ROA	-1.134***	-1.204***	-1.087***
Lev	-0.112	-0.112	-0.083
Top5	0.083	0.062	0.084
Big4	0.075*	0.096**	0.055
Cashflow	0.659***	0.548***	0.565***
_cons	0.408*	0.569**	0.502**
Observations	2,381	2,381	2,381
Adj.R2	0.202	0.225	0.201
F	46.19	18.37	45.8

***, **, and * denote significance at 1%, 5%, and 10%, respectively.

Columns (1) and (2) show that the coefficients for executives' overseas backgrounds are -0.434 and -0.382, respectively, both significant at the 1% level, indicating a significant negative impact on budget slack, supporting Hypothesis H1. Columns (3) show that the coefficient for risk-taking is -0.238, significant at the 5% level in column (3), albeit with reduced significance. Higher executive risk-taking is associated with lower budget slack, indicating a substitution effect.

② Mediation Effect Test

To test whether risk-taking mediates the relationship, the pathway "executives' overseas backgrounds → risk-taking → budget slack" is examined. Slack replicates the main regression. Risk shows that the coefficient for executives' overseas backgrounds is 0.061, significant at the 5% level, indicating that overseas backgrounds enhance risk-taking. Slack includes both executives' overseas backgrounds and risk-taking as independent variables. The coefficient for risk-taking is significantly negative, suggesting that overseas backgrounds reduce budget slack by increasing risk-taking. The coefficient for executives' overseas backgrounds remains significantly negative, indicating partial mediation, supporting Hypothesis H2.

5. Conclusion

This study examines how executives' overseas backgrounds affect corporate budget slack using 2016–2022 A-share listed firm data. Findings show: (1) Overseas backgrounds reduce budget slack by increasing risk-taking, with environmental uncertainty strengthening this effect. (2) The effect is stronger in non-SOEs, small firms, and weakly supervised firms.

Recommendations: (1) Diversify executive teams by hiring overseas talent to improve decision-making and budget governance. (2) Provide overseas training for local executives and support cultural adaptation for foreign-hired executives. (3) Strengthen oversight mechanisms to curb opportunism and enhance performance. Small firms should foster inclusive cultures to align organizational goals.

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The Impact of Soft Budget Constraints on Corporate Innovation

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Abstract. Innovation is the core driver of China's high-quality development and a critical support for maintaining the dual-circulation economic security framework. Enhancing corporate innovation capabilities has thus become a pressing issue. This study examines A-share listed companies in Shanghai and Shenzhen stock markets from 2010 to 2022, grounded in behavioral economics theory, using deductive reasoning and empirical research methods, to explore the impact of soft budget constraints (SBC) on corporate innovation and its mechanisms. The findings reveal a positive correlation between SBC and corporate innovation. Mechanism tests indicate that executive risk preferences and overconfidence partially mediate this relationship, with SBC improving innovation through these two behavioral pathways. Additionally, executives' overseas experience and media attention significantly positively moderate the SBC-innovation relationship. Heterogeneity analysis shows that firm size, technological dependence, and regional factors influence this relationship. Further research demonstrates that SBC enhances corporate innovation resilience. This study provides theoretical support for firms to strategically leverage SBC and gain a competitive edge in innovation markets.

Keywords. Soft budget constraints; Risk preference; Overconfidence; Economic cycles; Innovation resilience

1. Introduction

In China's dual circulation context, corporate innovation is crucial for high-quality economic development. While existing studies examine innovation through financing and governance factors, the government-market interaction remains overlooked. Soft Budget Constraints (SBC) - a transitional policy tool - presents dual effects: easing financing to spur innovation while potentially distorting incentives through information asymmetry. This study addresses the research gap by investigating SBC's impact on corporate innovation resilience through behavioral economics lens, incorporating upper echelons theory to analyze how executive risk preferences and overconfidence mediate this relationship. Focusing on China's A-share listed companies, the research explores SBC's mechanisms in shaping innovation strategies, considering prior findings on executive characteristics' correlation with budget slack. The results aim to provide practical guidance for optimizing corporate innovation policies and refining government budget management approaches, ultimately contributing to China's innovation-driven development strategy implementation under contemporary economic transitions.

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2. Research Mechanism and Hypotheses

2.1 Soft Budget Constraints and Corporate Innovation

SBC, as a government support mechanism, fosters corporate innovation by ensuring stable funding, easing financing constraints, and reducing innovation failure risks[1]. It signals executives that innovation investments are backed, effectively underwriting potential failures. SBC impacts innovation through two channels: First, following resource-based theory, SBC alleviates financing constraints—a major innovation barrier —particularly crucial in China's "difficult and expensive financing" context[2]. Through subsidies or investments, SBC provides low-cost resources, expanding firms' production possibilities and enabling strategic reallocation toward innovation [3]. This lowers financing costs and boosts innovation investment margins. Second, per upper echelons theory, SBC reshapes managerial decisions via mental accounting:(1)Executives perceive government-funded SBC as "lower-value" resources, increasing willingness to allocate them to high-risk innovation. (2)Diminishing sensitivity reduces aversion to incremental innovation spending after initial outlays. (3)Innovation's "payment isolation" (decoupled costs/benefits) shifts focus to outputs, easing psychological burdens.

Moreover, SBC's implicit government backing signals tolerance for failure, aligning with innovation-driven policies[4]. This encourages breakthrough innovations by mitigating executives' risk aversion. However, while SBC provides critical support, its effectiveness depends on balancing resource infusion with market discipline to avoid moral hazard. Therefore, we propose **H1:** The degree of SBC is positively correlated with corporate innovation.

2.2 Mediating Roles of Risk Preferences and Overconfidence

Behavioral economics posits that risk preferences and overconfidence are key psychological factors influencing decision-making[5] and significantly impact corporate strategic decisions.

Risk-seeking executives drive innovation by favoring high-risk R&D for competitive gains, improving innovation performance through greater failure tolerance[6]. SBC reinforces this by providing government-backed resources, lowering perceived innovation costs and boosting risk-taking. Signaling theory indicates SBC attracts external investors, further elevating risk appetite and innovation opportunities. However, innovation-driven policies may backfire: subsidies and tax incentives reduce failure costs, prompting overconfident executives to divert resources from R&D to financial investments, stifling innovation [7]. Overconfidence also distorts resource allocation by inflating self-assessment and underestimating risks. SBC mitigates this by incentivizing banks to extend loans, raising leverage risks that temper overconfidence. This pressures executives to enhance information reliability and adopt more balanced innovation strategies. Thus, while SBC encourages risk-taking, it also curbs overconfidence's negative effects, optimizing innovation incentives under government support[8]. Therefore, we propose **H2a:** SBC enhances corporate innovation by increasing executives' risk preferences. **H2b:** SBC enhances corporate innovation by reducing executives' overconfidence.

3. Research Design

3.1 Data Sources and Sample Selection

This study uses annual data from A-share listed companies in Shanghai and Shenzhen from 2010 to 2022. The sample was filtered as follows: (1) Exclude ST, *ST, and PT firms; (2) Remove financial and insurance firms; (3) Exclude firms with missing data. To mitigate outliers, all continuous variables were winsorized at the 1% and 99% levels, resulting in an unbalanced panel dataset. Interest expense data were sourced from the Tonghuashun database, while patent applications and other financial data came from CSMAR and East Money. Regression analysis was conducted using STATA 17.0.

3.2 Variable Definitions

Corporate Innovation (Innovation): Measured as the natural logarithm of total patent applications plus 1. **Soft Budget Constraint (SBC):** Calculated as the industry average of interest expense to total liabilities minus the firm's ratio[9]. A higher difference indicates stronger SBC. **Executive Risk Preference (MIRP):** Evaluated using principal component analysis across six indicators: risky asset ratio, leverage, core profitability, retained earnings, self-funding sufficiency, and capital expenditure [10].

$$\mathrm{MIRP} = 0.3046x_1 + 0.1779x_2 + 0.1368x_3 + 0.1378x_4 + 0.1262x_5 + 0.2369x_6$$

Overseas Background (Ove): Proportion of executives with overseas experience. **Media Attention (Media):** Natural logarithm of annual media coverage plus 1.ROA, fixed asset ratio, growth (revenue growth), board size, management shareholding, top 10 shareholders' concentration, CEO duality, and firm age.

3.3 Model Specification

(1) Baseline Model (Testing H1):

$$\mathrm{Innovation}_{i,t} = \beta_0 + \beta_1 \mathrm{SBC}_{i,t} + \sum \mathrm{Controls} + \sum \mathrm{Ind} + \sum \mathrm{Year} + \varphi$$

Where **i** represents the individual firm, and **t** represents the year; Innovationi,t is the dependent variable, indicating the innovation output of listed company **i** in year **t**;SBCi, t is the core independent variable, representing the degree of soft budget constraints faced by listed company **i** in year **t**;∑Controls denotes the control variables selected earlier;
∑Ind and ∑Year represent industry and year fixed effects, respectively;φ is the random error term.If β1 is significantly positive, it indicates a significant positive correlation between soft budget constraints and corporate innovation; otherwise, the relationship is negative or insignificant.

(2) Mediation Model for Risk Preference (H2a):

$$\mathrm{MIRP}_{i,t} = \alpha_0 + \alpha_1 \mathrm{SBC}_{i,t} + \sum \mathrm{Controls} + \sum \mathrm{Ind} + \sum \mathrm{Year} + \varphi$$

$$\mathrm{Innovation}_{i,t} = \omega_0 + \omega_1 \mathrm{SBC}_{i,t} + \omega_2 \mathrm{MIRP}_{i,t} + \sum \mathrm{Controls} + \sum \mathrm{Ind} + \sum \mathrm{Year} + \varphi$$

Mediation Model for Overconfidence (H2b):

$$OC_{i,t} = a_0 + a_1 SBC_{i,t} + \sum Controls + \sum Ind + \sum Year + \varphi$$

$$Innovation_{i,t} = b_0 + b_1 SBC_{i,t} + b_2 OC_{i,t} + \sum Controls + \sum Ind + \sum Year + \varphi$$

Interpretation:

If α1 (SBC → MIRP) and ω2 (MIRP → Innovation) are both significant, **risk preference** mediates the relationship. If a1 (SBC → OC) and b2 (OC → Innovation) are both significant (with a1 expected to be negative), **overconfidence** mediates the relationship. If ω1 or b1(direct SBC effects) become insignificant upon adding mediators, **full mediation** is achieved; otherwise, **partial mediation** exists.

4.Empirical Analysis

4.1 Benchmark Regression

(1) Main Regression Effect

Table 1. The Impact of Soft Budget Constraints (SBC) on Corporate Innovation

Variable Category	(1) Innovation	(2) Innovation	(3) Innovation
SBC	0.155***	0.882***	0.883***
ROA		0.465***	0.797***
FirmAge		0.645***	0.445***
Mshare		0.053*	-0.295***
_cons	1.121***	1.587***	1.397***
Adj.R2	0.002	0.025	0.214
F	49.75	74.19	176.8

***, **, * denote statistical significance at 1%, 5%, and 10% levels respectively (t-values in parentheses)

Key Findings:

H1 Confirmation: SBC shows consistently positive and significant coefficients (0.155 to 0.883) across all specifications, robust to control variables and fixed effects ($p<0.01$). This strongly supports Hypothesis 1 that soft budget constraints promote corporate innovation. **Economic Significance**: The coefficient magnitude increases substantially (5.7-fold) when accounting for firm characteristics and fixed effects, suggesting SBC's innovation-enhancing effect is amplified in properly specified models.

Model Fit Improvement:

Adjusted R^2 jumps from 0.2% to 21.4% in the full model. F-statistic increases from 49.75 to 176.8, indicating superior explanatory power

(2) Mediating Effect

Risk Preference Pathway (H2a):

Stage 1 (SBC→Innovation): 0.883*** ($p<0.01$).Stage 2 (SBC→MIRP): 0.078*** ($p<0.01$).Stage 3 (MIRP→Innovation): 0.043*** ($p<0.01$).Mediation Effect: $0.078 \times 0.043 = 0.0034$ (3.4% of total effect).**Conclusion**: Partial mediation supported (Sobel $z=3.21$, $p<0.01$)

Overconfidence Pathway (H2b):

Stage 1 (SBC→Innovation): 0.883*** ($p<0.01$).Stage 2 (SBC→OC): -0.030*** ($p<0.01$).Stage 3 (OC→Innovation): -0.631*** ($p<0.01$).Mediation Effect: $-0.030 \times -0.631 = 0.0189$ (21.4% of total effect). **Conclusion**: Partial mediation supported (Sobel $z=3.78$, $p<0.01$)

Key Findings:

Dual Pathways Confirmed:SBC → ↑Risk Preference → ↑Innovation (H2a).SBC → ↓Overconfidence → ↑Innovation (H2b).

4.2 Robustness Checks

Table2. Robustness Checks

Specification	**(1) Alternative SBC Measure**	**(2) Excluding Crisis Years**	**(3) Province & Firm FE**
SBC Coefficient	0.119***	0.796***	0.465***
Observations	25,939	18,967	25,939
Adjusted R^2	0.200	0.147	0.078
F-statistic	162.2	97.04	29.47

Robustness Test Results: We validate our findings through three robustness tests: (1) Using Zhou & Li’s (2006) binary SBC measure (negative net income), results remain significant (0.119***), though effect sizes differ due to measurement granularity. (2) Excluding crisis periods (2015, 2020–2022) yields stable coefficients (0.796 vs. baseline 0.883), confirming resilience to economic shocks. (3) Adding province/firm fixed effects accounts for 89% regional and 76% firm heterogeneity, with slightly attenuated but significant results, ruling out regional/firm-specific biases. All models show consistent significance ($p < 0.01$), with 47% of effects driven by time-varying factors.

5 Conclusions and Implications

This study extends the theory of soft budget constraints (SBC) to the field of innovation resilience, revealing its dynamic moderating role in the VUCA era (Volatility, Uncertainty, Complexity, and Ambiguity), while refining the heterogeneous analysis framework across three dimensions: firm size, technological dependence, and regional economic disparities. Using unbalanced panel data from Shanghai and Shenzhen A-share listed companies (2010–2022), we investigate the impact of SBC on corporate innovation and its mechanisms. Heterogeneity analysis is conducted by categorizing samples based on firm size and technological dependence.

5.1 Key findings

(1)SBC promotes corporate innovation: A significant positive correlation exists between SBCand innovation input/output.(2)**SBC enhances innovation resilience**: It helps firms withstand environmental uncertainties, particularly during economic turbulence.**(3)Threshold effects are observed**:SBC boosts innovation in large firms but inhibits it in small firms, likely due to resource redundancy and management efficiency trade-offs. Technological dependence: SBC significantly promotes innovation in non-high-tech firms, while its effect is insignificant in high-tech firms.SBC significantly fosters innovation in eastern, central, and western China but not in the northeast, possibly due to weaker institutional environments (e.g., lower marketization indices).

5.2 Theoretical Contributions

This study contributes to: **(1) Dynamic perspective**: Extends SBC research from static resource allocation to innovation resilience in VUCA contexts. **(2) Boundary conditions**: Validates the Resource-Based View (RBV) in SBC studies through size threshold effects. **(3) Policy insights**: Provides micro-level evidence for designing "effective market + proactive government" innovation policies in transitional economies.

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Organizational Structure and Institutional Design of Cross Border Data Services in the Guangdong Hong Kong Macao Greater Bay Area–Taking the Offshore Data Center of Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone as an Example

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Abstract. The “Institution Lag” between the demand for cross-border data services and the supply of rules constrains the in-depth development of cross-border data flow. The Guangdong Hong Kong Macao Greater Bay Area, as a strategic region with the highest degree of openness, the most significant institutional differences, and full of vitality and international competitiveness in China, has a particularly prominent internal tension between the autonomy demand for cross-border data flow and institutional standardization. This study takes the offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone as an example, and combines the theory of ecological niche construction and organizational configuration to propose an analytical framework of "cross-border organizational configuration based on ecological niche construction". It analyzes the conditional constraints of cross-border data flow in the Guangdong Hong Kong Macao Greater Bay Area and the establishment process of offshore data centers, explores the organizational configuration and institutional innovation mode of the data cross-border service system, and proposes to optimize the ecological niche construction of data cross-border services from the aspects of dislocation development, replenishment development, borrowing development, and expansion and expansion, in order to seek the best balance point between cross-border data flow security and freedom, promote the marketization and globalization of data elements.

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Keywords. Guangdong-Hong Kong-Macao Greater Bay Area, Cross Border Data Flow, Offshore Data Center, Organizational Configuration, Niche Construction

1. Introduction

In the context of accelerated global digital transformation, the orderly cross-border flow of data has strategic significance for cultivating a unified data market, promoting the free flow of factors, promoting industrial upgrading, and regional coordination. As a key infrastructure for cross-border data flow, offshore data centers provide crucial cross-border data services, and their development and layout are receiving widespread attention. As one of the most economically dynamic and innovative regions in China, the Guangdong Hong Kong Macao Greater Bay Area has unique advantages and opportunities in the field of cross-border data flow. However, it also faces practical challenges such as the rise of the digital economy and the surge in demand for cross-border data flow. The offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone, as an institutional innovation and policy pilot in the Guangdong Hong Kong Macao Greater Bay Area, helps explore the Chinese model of innovation and organizational change in cross-border data flow services, provides a demonstration for cross-border data governance in the Guangdong Hong Kong Macao Greater Bay Area and even the whole country, and provides experience reference for the marketization and globalization of data elements in China. However, cross-border data flow has always been in conflict with liberalization and localization, strict restrictions and loose access, and standardization and autonomy. These are essentially institutional lags between cross-border data service rules and the development of the digital economy. It is urgent to form a comprehensive and reasonable institutional supply in terms of organizational structure and rule arrangement to promote the dynamic balance between security and development in cross-border data flow, and to achieve effective flow of data elements in the global market. This study examines a typical case in China's Guangdong-Hong Kong-Macao Greater Bay Area: the Lok Ma Chau Shenzhen-Hong Kong Innovation and Technology Hub's offshore data center. It aims to explore the possibility and feasibility of cross-border data flows in complex institutional settings, and to figure out how cross-border data services can gradually adapt to and balance normativity and autonomy. The exploration is highly exemplary and offers a good reference for policy design and institutional arrangements for cross-border data flows in the global era.

2. Question Raised: How Can Cross-Border Data Flows Achieve Autonomy Within Norms

Cross Border Data Flow is a special case of data element flow, specifically referring to the flow of data across national borders. Cross border data flow mainly includes operations such as data transmission, access, storage, and editing, which can drive digital data flow, knowledge flow, and value flow, and promote value exchange between data users and data holders. However, cross-border data flows always face obstacles from sovereign regulations and technical standards, reflecting a clear conflict between normativity and autonomy. The former reflects considerations of national security and government regulation, while the EU strengthens the rigidity of data sovereignty through the General Data Protection Regulation (GDPR), and China's Data Security Law and Personal Information Protection Law emphasize the priority of national security; The latter reflects the market operation and the flow demand of data elements. In the conflict between security logic and market logic, global cross-border data flows are facing challenges such as fragmented rules and ambiguous regulations, which constrain the development process of global data element marketization. How to better leverage the government's institutional construction and rule supply in cross-border data flow is an important question that urgently needs to be answered by the global governance system for cross-border data flow. [1]

Offshore data centers are becoming a "green channel for cross-border data flow", playing an important role in promoting cross-border digital trade, facilitating Chinese enterprises to go global, and advancing dual circulation. In recent years, Shanghai, Guangdong, Zhejiang, Hainan and other provinces and cities have proposed or are carrying out offshore data center construction. As a key infrastructure for cross-border data flow, offshore data centers need to utilize data center facilities in specific areas (with "domestic and foreign" characteristics) to directly exchange information with the uplink network through dedicated international communication channels. They provide placement, proxy maintenance, system configuration, and management services for servers and other equipment of non-domestic users, as well as rental of database systems or servers and storage space, proxy rental of communication lines and export bandwidth, and other application services. "Pilot" is a progressive solution. Compared to "breakthrough innovation" or "creative destruction", policy experimentation is more prudent. The Shenzhen Hetao Shenzhen Hong Kong Science and Technology Innovation Cooperation Zone, as an experimental field for institutional innovation under the framework of "One Country, Two Systems", carries the important mission of "breaking through" and "opening up" cross-border data flow in the Guangdong Hong Kong Macao Greater Bay Area. Taking the construction of offshore data centers in the Hetao Shenzhen Hong Kong Science and Technology Innovation Cooperation Zone as a pilot sample, relying on the cross-border collaboration model of "one zone, two parks" and "domestic and foreign", we have taken the lead in exploring an effective mechanism for promoting cross-border data flow through the construction of offshore data centers, which will provide a demonstration experience for institutional innovation in the cross-border flow and collaborative governance of data elements in global urban agglomerations.

However, in the context of multiple institutional constraints and complex organizational networks, how can the offshore data center of the Hetao Shenzhen Hong Kong Science and Technology Innovation Cooperation Zone break through the normative constraints of different systems and achieve controllable autonomy? How to reconstruct the cross-border data service system through institutional innovation and organizational design? What organizational configuration model and path did the construction process of offshore data centers follow? Taking cross-border data services in the Guangdong Hong Kong Macao Greater Bay Area as an example, how should we optimize cross-border data services under multiple institutional constraints in the future? How to balance the relationship between security risks and free flow in cross-border data flow at the institutional design level?

To answer the above questions, the author conducted an in-depth observation of the institutional design process of the offshore data center in the Hetao Shenzhen Hong Kong Science and Technology Innovation Cooperation Zone, from concept proposal to overall planning. The Lok Ma Chau Shenzhen-Hong Kong Innovation and Technology Hub, a key part of the Guangdong-Hong Kong-Macao Greater Bay Area, boasts unique geographical and policy advantages. Underpinned by the complex “One Country, Two Systems” framework and the innovative “Domestic with a Customs Exemption” model, it offers an ideal pilot setting for building offshore data centers. Combining relevant in-depth interviews and field research, and combining ecological niche construction theory and organizational configuration theory, the author proposed the "Cross border Organizational Configuration Based on Ecological Niche Construction" as an analytical framework to summarize the ecological niche construction of cross-border data flow in the Guangdong Hong Kong Macao Greater Bay Area, providing theoretical basis and practical paradigm for the institutional design of cross-border data flow.

3. Literature Review: Institutional Gaps And Service Demands In Cross-Border Data Flow

Data elements also pose data security risks due to their high liquidity. [2] Cross border data flow faces the challenge of balancing security and freedom, and there is a strong demand for legal legislation, internal compliance, and administrative supervision. Data has dual attributes of information and power, as well as diverse characteristics such as development value, security risks, and market mechanisms. Existing research has generally discussed the institutional gaps and service demands of cross-border data flows, and has been thinking about how to strike a balance between security and freedom in cross-border data flows.

The United States and the European Union, as pioneers, have formed relatively mature regulatory systems. The United States upholds the "data freedom theory" and emphasizes the market value and economic benefits of data, while the European Union is based on the "data sovereignty theory" and focuses on the protection of personal data privacy. There are differences in values, regulatory paths, and institutional designs between the United States and Europe, and both sides are in a game state in global data governance. The control rules for high-intensity data flow in China are not coordinated with the needs of digital trade development. By comparing the exception clauses of cross-border data flow trade regulations in WTO, CPTPP, and RCEP, it was found that the principle of exception plays a role in balancing personal privacy, national security, and the free flow of data. [3] From the perspective of game theory, the essence of cross-border data flow policies is to balance interests, involving conflicts between data sovereignty, security, and free flow. Countries are considering how to choose strategies that maximize their interests.

It can be observed that global governance of cross-border data flows exhibits strong regulation and fragmentation. Countries actively optimize their own cross-border data flow regulation while effectively maintaining data security and personal privacy protection. However, there are problems such as weak regulatory agencies and single regulatory methods for cross-border data flow. [4] This means that there is insufficient institutional construction for cross-border data flow, facing a clear gap between rules and reality. This reflects the "impossible triangle" of cross-border data flow, where data autonomy, data protection, and data flow cannot be achieved simultaneously. [5] It can also be understood that there are "three difficult choices" in the regulation of cross-border data flow, which cannot simultaneously balance "good data protection", "free flow of cross-border data", and "data protection autonomy". [6] China's cross-border data flow faces a conflict between institutional data sovereignty and open demand, as well as a contradiction between strict regulation and free openness. [7]

On top of the common challenges faced by cross-border data flow in our country, the Guangdong Hong Kong Macao Greater Bay Area also faces a special environment of "one country, two systems, and three legal domains", which leads to a lack of consensus in the top-level design of data governance, conflicting rules, and insufficient linkage of regulatory mechanisms. Someone found significant differences in legislative protection levels, cross-border flow mechanisms, and regulatory agencies between Guangdong and Macao when observing cross-border data flow hubs in the Hengqin Shenzhen Cooperation Zone, leading to obstacles in cross-border data flow. [8] In response to this, scholars have attempted to construct cross-border data governance in the Guangdong Hong Kong Macao Greater Bay Area based on multiple dimensions such as institutional supply, governance framework, and guarantee system. It is urgent to use institutional supply to break the "impossible triangle", construct a system of data flow and security rules, and improve cross regional collaboration mechanisms to achieve orderly and secure cross-border data flow. [9]

In summary, existing research has provided rich and in-depth theoretical thinking and empirical references, laying a solid foundation for this study. However, there are few studies that truly open up the institutional design and actual operation process of cross-border data flow, and there are also few studies that conduct organizational analysis of different cross-border data service institutions from a comparative perspective. Therefore, the institutional supply and rule design of cross-border data flow still remain at the macro level, without delving into the rich and specific micro level. How to analyze the specific model of offshore data centers reconstructing the cross-border data service system through institutional innovation and organizational design from a more dynamic and clear perspective when facing practical challenges such as poor legal connection, inconsistent data classification standards, and insufficient international rule integration in the Guangdong Hong Kong Macao Greater Bay Area cross-border data flow is a more important and critical research issue. [10] This allows for a deeper exploration of the institutional and service - support factors that contribute to successful cross - border data flows.. When building offshore data centers and conducting cross-border data services, it's essential to account for internal and external differences. For comparing with similar service institutions and identifying competitive advantages, the study incorporates the analytical perspective of ecological niche construction theory.

4. Analysis Framework: Cross Boundary Organizational Configuration Based on Ecological Niche Construction

Niche Construction Theory emphasizes that the subject actively transforms the environment to form a dynamic feedback mechanism and create new ecological niches, while Organizational Configuration Theory focuses on the adaptability of organizational structure to the external environment. [11] In the cross-border data scenario, how data cross-border service institutions form a sustainable living space through strategic positioning and institutional games is still an unexplored "black box".

4.1 Theoretical Basis: Ecological Niche Theory and Organizational Configuration Theory

Niche Theory is one of the core theories in ecology, mainly used to describe the roles of species in ecosystems, their resource utilization patterns, and their relationships with other species. The core idea is that each species has a unique "position" and "survival strategy" in the ecosystem, and coexistence is achieved through differentiated competition. Ecological niche theory is often used to explain the competitive and cooperative relationships between organizations, cities, or regions. [12] Therefore, these modified ecological niches will come back to shape the adaptability of their offspring (and other organisms). This is common in human life, especially in inter - city competition and international relations. In short, organisms co evolve with their environment.

The concept of Organizational Configuration was first proposed and introduced into the field of organizational management research by Danny Miller and his collaborators. [13] Organizational systems are viewed as tightly coupled aggregates in a bidirectional causal cycle. Organizational configuration is relatively stable, but this stability is not a static equilibrium, but a dynamic stability composed of changes within the configuration and transitions from one configuration to another, manifested as a punctuated equilibrium process as a whole. The driving force behind the evolution of configuration comes from the contrast between the forces that disrupt the internal and external balance of the organization, trigger change, and maintain the status quo and resist change. When the force that triggers change is significantly stronger than the force that resists change, configuration undergoes significant changes. However, in most cases, the inertia force of the organization dominates and presents stability. Take the operation of ecological and environmental departments as an example. Organizational configuration theory can be used to explain why ecological and environmental governance adopts an overall design of a “super ministry system.” This reflects that when government organizations face new environments and conditions, once the power of change and innovation overcomes the stubborn factors, they will use systematic thinking to promote smooth and dynamic departmental transformation.

4.2 Integrated Framework: Building Ecological Niches in Cross Border Organizations

Combining the application scenarios of cross-border data flow, the organizational configuration process based on ecological niche construction occurs more frequently in specific cross-border processes, which requires going beyond the original internal boundaries of the organization and breaking through the rule resistance of different institutional constraints. [14] Combining ecological niche construction and organizational configuration theory, construct a cross-border organizational configuration framework of "subject agency institutional adaptation system feedback". Firstly, the dimension of subject agency. Actively shaping the "ecological niche" of cross-border data flow through institutional innovation and rule setting, attracting top international research institutions, data vendors, and multinational enterprises to gather. Secondly, the dimension of institutional adaptation. Relying on cross-border data trading and circulation platforms, we will promote data classification authentication and mutual recognition of privacy calculation standards, form a "domestic and foreign" special supervision zone, dynamically adjust the "whitelist" access scope, and achieve cross regional rule connection. Thirdly, the dimension of system feedback. By aggregating cross-border data elements, promoting technological innovation iteration and digital economy development, the self - optimization of the cross-border data flow system is naturally achieved through positive feedback. Finally, continuously expanding the breadth of ecological niches, identifying the relative competitive advantages of ecological niches through differentiated positioning, reducing the risk of ecological niche overlap, and enhancing ecological niche inclusiveness based on institutional complementarity.

5. Innovation Experiment: Organizational Configuration of Offshore Data Center in Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone

As an important infrastructure for cross-border data flow, offshore data centers play a significant role in promoting regional economic development and enhancing international competitiveness. As an important part of the Guangdong Hong Kong Macao Greater Bay Area, the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone has unique geographical advantages and policy support, making it an ideal pilot choice for building offshore data centers. During the pilot exploration of the offshore data center in the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone, the organizational configuration was mainly carried out from the aspects of development conditions, preliminary foundations, and operational implementation plans.

5.1 Ecological Niche Advantage

5.1.1Advantages of institutional authority

Compared with other regions, the Hetao Shenzhen Hong Kong Science and Technology Innovation Cooperation Zone has unique advantages in "cross-border, cross institutional, and cross tariff zones", which also provides convenient conditions for exploring mechanisms, norms, and standards for data export in the future, and conducting pilot projects for data cross-border transmission security management. In terms of trial and error, Shenzhen, as an economic special zone, has a certain degree of autonomy, while the Hetao Cooperation Zone has relatively greater freedom. On the premise of following the basic principles of the Constitution, laws, and administrative regulations, the Hetao Cooperation Zone fully utilizes the legislative power of the Shenzhen Special Economic Zone, allowing Shenzhen to base itself on the needs of reform and innovation practices in the Shenzhen industrial park, and make flexible provisions for laws, administrative regulations, and local regulations based on authorization.

5.1.2Advantages of being adjacent to Hong Kong and Macau

The Shenzhen Park is separated from the Hong Kong Park by a river and directly borders the border. It has two land ports, Futian Port and Huanggang Port, connecting Shenzhen and Hong Kong, making it the most direct docking point for Shenzhen Hong Kong technological innovation cooperation. It has the special advantage of integrating advantageous industrial resources in the Guangdong Hong Kong Macao Greater Bay Area, gathering global technological innovation elements, and linking international and domestic markets. Through various efforts such as spatial transformation and policy superposition, it attracts the gathering and development of scientific and technological innovation resources, and the concentration of innovation in the park continues to increase.

5.1.3Technological innovation and industrial advantages

At present, Hetao has gathered more than 160 high-end scientific research projects, 13 domestic and foreign academicians and experts, 15000 scientific research talents, including 8 national level major scientific research platforms; 13 research institutions in Hong Kong universities. In terms of computing power, the "Hetao Artificial Intelligence Computing Power Platform" has been launched, which can coordinate and dispatch the optimal computing power with a scale of nearly 5000P; In terms of data circulation, as of May 2024, the Shenzhen Data Exchange has completed a total of 63 cross-border data transactions on the exchange, with a cumulative transaction amount of 145 million yuan.

5.2 Ecological Niche Disadvantage

5.2.1 Insufficient Network Communication Infrastructure

Network communication infrastructure is the most basic ICT requirement for offshore data centers, and currently Hetao has shortcomings in this area. First, the Internet data transmission channel has not been built yet. One of the key competitive advantages that offshore data centers attract enterprises is the provision of low latency, low packet loss rate, and high security data services, which are highly dependent on dedicated international data transmission channels for implementation. This channel is a dedicated link for the construction of export-oriented industrial parks directly to China's Internet International Gateway Bureau, which has a certain degree of exclusiveness and can significantly reduce the website access delay. Secondly, there is currently no submarine cable landing station or international import and export bureau in Shenzhen. As the main way of international communication, the construction of submarine cables can significantly improve the level of network interconnection between countries, which is of great significance for the construction of offshore data centers. We see that Singapore, Hong Kong, and Shanghai all have significant advantages in this regard.

5.2.2 Physical Space and Power Supply Face Certain Constraints

Firstly, the physical space of the Hetao Shenzhen Industrial Park is relatively limited. Data centers typically require large areas to accommodate server rooms, backup generators, cooling systems, and other facilities, which are often located on the outskirts of cities or in remote areas. Land resources are relatively scarce, and acquisition and development costs are high. Secondly, the power supply also faces challenges. Offshore data centers are high energy consuming facilities, with electricity related costs accounting for the largest proportion of data center construction costs, reaching 69%; And electricity costs also account for a large proportion of operating costs, reaching 56.7%. As a densely populated metropolis, Shenzhen has a huge demand for electricity. At the same time, as a low latitude city, the high daily temperature leads to high cooling costs. How to further improve the energy efficiency ratio of data centers is a challenge.

5.2.3 Offshore Data Center Business Faces Strong Competition

From a domestic perspective, Chongqing and Nanjing in Jiangsu have already built offshore data centers, while Shanghai, Yunnan, Zhejiang, Hainan and other provinces and cities are also advancing related plans. Overseas, Singapore and Hong Kong are the largest data centers in the Asia Pacific region. As a latecomer, Shenzhen needs to find differentiated advantages in infrastructure, technology, price, and industrial ecology to attract overseas IDC business to migrate locally. For example, in terms of electricity prices, domestic electricity prices have a comparative advantage over other regions overseas. In addition, Shenzhen also has obvious industrial advantages in electronic information, green low-carbon, and energy storage industries, which can provide technical support and innovative solutions for offshore data centers, promote the technological upgrading, intelligence, and green sustainable development of offshore data centers.

5.3 Experience of the Same Rank

Prior to the pilot exploration of offshore data centers in the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone, several provinces and cities in China have also carried out innovative explorations such as international (offshore) data center pilot and cross-border two-way data circulation, and have accumulated a considerable amount of pilot experience. Inspired by the development experience of offshore data centers at the same level in China, the offshore data centers in the Hetao need to absorb and transform the following pilot experiences:

Firstly, make reasonable use of location advantages. With the geographical advantage of being adjacent to Hong Kong, Hetao Cooperation Zone has the natural conditions to connect with the Internet. The "One River, Two Banks" plan has created a unique institutional environment of "One Country, Two Systems" in Hetao. The cooperation zone has two systems, two tariff zones, two currency systems, and two laws, which provide important conditions for cross-border data flow and the construction of offshore data centers. The offshore data center of Hetao Science and Technology Innovation Cooperation Zone has outstanding location advantages. The Shenzhen Park is separated from the Hong Kong park by a river, making it the most direct contact point for Shenzhen Hong Kong science and technology innovation cooperation, with superior cross-border cooperation conditions.

Secondly, establish a dedicated channel for cross-border data flow. Build a new type of data infrastructure within the park that can provide functions such as secure storage, authorization, authentication, and trusted transmission of data. Accelerate the construction of a trustworthy circulation environment, and implement two basic infrastructures including a comprehensive privacy computing platform to achieve customized cross-border trusted data transmission. Support the construction of international data dedicated channels in the Shenzhen industrial park, and explore the construction of international information and communication facilities such as the International Communication Import and Export Burea.

Thirdly, carry out data classification and grading management. The Regulations on Promoting and Regulating Cross border Data Flow clearly stipulate the classification and grading of data, the establishment of a "positive list" and "negative list" for data export, and the establishment of a model for important data catalogs and general data lists. It is necessary to explore the dynamic list of cross-border data transactions in combination with the actual needs of the Guangdong, Hong Kong and Macao Greater Bay Area in the financial, e-commerce, Internet, medical industry and other scenarios, so as to meet the outbound demand of enterprise data in a timely manner. We need to supervise every link from data generation to storage, transmission, processing, and use, and establish a data export security assessment system.

Fourth, promote pilot projects for cross-border data transactions. The Hetao Cooperation Zone has piloted cross-border data trading, supported the construction of the Shenzhen Data Exchange, and cultivated cross-border data service providers. Establish a cross-border data zone, mass market cross-border data product services, release the "first public welfare cross-border data security consulting service", and assist enterprises in solving cross-border data problems. Promote the establishment of Shenzhen Hong Kong data cross-border transaction liaison mechanism, encourage enterprises to carry out data cross-border transaction cooperation, encourage enterprises in both places to carry out data cross-border transaction cooperation, and advocate RMB settlement for cross-border data transactions in financial, e-commerce, Internet, medical industry and other scenarios. It is necessary to form a graded and hierarchical policy support plan at the levels of the Greater Bay Area, provinces, and cities, and simultaneously explore the data circulation mechanism in the Greater Bay Area.

5.4 Systematic Configuration

After clarifying functional requirements, identifying its own strengths and weaknesses, and conducting peer experience learning and feasibility studies, the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone is advancing the implementation of offshore data centers towards the most critical organizational configuration stage, including rule establishment, institutional setup, and business operation, forming a set of implementation plans for construction and operation.

5.4.1 Construction Plan

Hetao Shenzhen Park will build an offshore data center pilot area, which is divided into an onshore service area and an offshore service area. It will implement physical isolation of the Internet, focus on key scenarios, and build an international data service and computing service hub. Hetao Shenzhen Park uses the corresponding computer room facilities in special areas (with the characteristics of "domestic customs area") to provide offshore data services through the dedicated Internet data channel. It is divided into an onshore service area and an offshore service area. The onshore service area interacts with other areas in China, and the offshore service area and overseas data basically enter and exit freely. The two are physically isolated from the Internet.

There are three key points in operation: Firstly, for data outside the positive list or within the negative list, the application for cross-border data security assessment, standard contracts, or personal information security certification needs to be completed when flowing from onshore to offshore service areas. Secondly, offline expert services refer to professional services provided by operating units without connecting to domestic or international networks, including data processing, data governance, auxiliary filing, and compliance review. Thirdly, drawing on the Development Regulations of Hainan Free Trade Port International Data Center, relevant enterprises can apply to access offshore data centers for data processing, machine learning, model training and other offshore data businesses.

5.4.2 Operation Plan

Firstly, at the institutional level, establish legal, secure, and convenient rules for cross-border data flow. One is to formulate the "Classification and Grading Management Measures for Cross border Data Flow in Hetao Shenzhen Industrial Park" to classify and manage cross-border data. The second is to compile a general data list and a key data directory, and implement positive to negative list management. Develop a negative list of data on your own, and data outside the negative list does not need to fulfill the obligation of evaluation, filing, and declaration for export. The third is to formulate the "Regulations on the Development of Offshore Data Centers in Hetao", which clarifies the business model, operational regulations, and regulatory requirements of offshore data centers. The fourth is to accelerate the integration of high standard economic and trade rules and international standardization systems. To benchmark against international high standard economic and trade rules such as DEPA and CPTPP.

Secondly, at the technical level, enhance the technical guarantee for the legitimate and secure flow of data. One is to build green and secure high-performance offshore data centers. The second is to speed up the opening of a dedicated Internet data channel. Priority shall be given to the organization of application for the special channel of low delay. The third is to enhance the technical support for the secure operation of offshore data centers. Set up an OSA offshore account, use offshore data centers to store and process data, and use strong encryption algorithms to protect the security of data during transmission and storage.

6. Institutional Design: Ecological Niche Construction of Cross-Border Data Services in The Guangdong Hong Kong Macao Greater Bay Area

Cross border data flow governance is the focus of a new round of international competition. For the offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone, it is necessary to promote the construction of ecological niche and make adaptive adjustments to the cross-border data governance model from the aspects of dislocation development, complementary development, borrowing development, and expansion, in order to form a differentiated competitive advantage in the global cross-border data flow system.

6.1 Misplaced Development

Differentiated competition is the core of differentiated development. In the field of cross-border data flow services, it is crucial to avoid functional overlap and achieve differentiated development. The offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone should conduct in-depth analysis of its similarities with other regions in terms of service content, target customer groups, technical standards, etc., to determine the degree of ecological niche overlap. A lower degree of overlap can help it avoid direct competition. At the same time, it is necessary to strengthen the competitiveness of its own ecological niche, and establish a competitive advantage in cross-border data flow by continuously innovating, optimizing services, and reducing costs to differentiate itself from competitors in terms of technology, services, and prices. In terms of differentiated positioning, the offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone should focus on the scenario of "cross-border interaction of scientific research data", such as the Guangdong Hong Kong Macao Greater Bay Area International Clinical Trial Institute, effectively avoiding homogeneous competition with Shanghai (focusing on financial data) and Hainan (focusing on game going global).

6.2 Supplementary Development

Filling in gaps is a key means of filling development gaps. By accurately identifying weak links in the flow of data elements in other regions within the area, such as institutional gaps and infrastructure shortcomings, the offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone provides corresponding services or technical support for supplementary development. To provide high-quality data storage, backup, and disaster recovery services for enterprises in other regions, filling the gaps in data security and reliability in these areas. The Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone can also give play to its own institutional innovation advantages, take the lead in formulating the Regulations on the Development of Hetao Offshore Data Center, fill in the institutional gaps in data classification and hierarchical protection and negative list management, and accelerate the construction of dedicated data channels for the Internet to complement the physical weakness of network communication infrastructure. The complementary development model can not only improve the structural imbalance of the data industry chain in the Guangdong Hong Kong Macao Greater Bay Area, but also strengthen the industrial complementarity with surrounding regions through differentiated functional synergy, ultimately achieving the overall improvement of the cross-border data element circulation system.

6.3 Borrowing Development

Resource collaboration is an important foundation for leveraging development. In the integrated development pattern of the Greater Bay Area, the offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone should fully seize the opportunity of "leveraging development". Through resource integration and collaboration, closely relying on the policy highland advantages, profound digital economy industry foundation, and strong international market demand influence of the Greater Bay Area, actively building deep cooperative relationships with other cities in the area, and achieving the sharing of resources, technology, and market elements. In terms of location coordination, we can fully develop and utilize Hong Kong's 11 submarine optical cable resources as an international communication hub, achieve efficient sharing with the International Communications Import and Export Bureau, and enhance the stability and security of cross-border data transmission. At the regulatory level, we actively draw on international advanced data protection experiences, such as the EU GDPR and Singapore's Personal Information Protection Act.

6.4 Expand and Increase Capacity

On the basis of dislocation, supplementation, and borrowing development, in order to achieve long-term sustainable development of cross-border data services, it is necessary to continuously expand capacity and add more new forms. That is, the offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone should continue to expand its business coverage and increase service space inclusiveness in cross-border data flow, thereby expanding the ecological niche width, covering diversified businesses such as data storage, processing, analysis, and trading, meeting the needs of different customers, enhancing the competitiveness of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone offshore data center in the data cross-border service market, attracting more enterprises to settle in, promoting data resource aggregation, circulation, and digital economy prosperity. This requires phased planning and promotion in the near and medium to long term.

Firstly, focusing on the short-term goal of institutional supply, implementing more open and convenient rules for cross-border data flow, accelerating the formulation of relevant management measures and development regulations, and compiling positive and negative lists for data export. Secondly, focusing on the medium and long-term goals of institutional design, building a cross-border data space network and an IDS trusted data space to achieve a balance between data sovereignty and circulation efficiency; Promote the sharing mechanism of computing power among Guangdong, Hong Kong, and Macao; Explore new mechanisms for cooperation between Shenzhen and Hong Kong offshore data centers, promote the construction of the Hetao Shenzhen Hong Kong International Data Port, accelerate mutual recognition, trust, and utilization between Shenzhen and Hong Kong; Improve trusted computing power trading services; Explore green channels for fixed network access to the Internet, carry out local targeted pilot projects, and optimize the security assessment system for cross-border data flow; Attempt to establish an international communication import and export bureau, actively seek support from higher-level units, and accelerate data exchange and collaborative cooperation with mainland operators.

7. Conclusion and Discussion

This study takes the offshore data center of the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone as an example, combining ecological niche construction and organizational configuration theory, focusing on the institutional design and organizational configuration of cross-border data flow in the Guangdong Hong Kong Macao Greater Bay Area, and systematically analyzing the optimization path of the data cross-border service system. Research has found that, firstly, the construction of ecological niches and differentiated competition are key points in the innovation of cross-border data service systems. It is necessary to strengthen regional synergies through "differentiated development," "complementary development," "borrowed development," and "expansion and addition," in order to enhance the overall ecological niche advantage of cross-border data flow in the Guangdong Hong Kong Macao Greater Bay Area. The framework of "cross boundary organizational configuration based on ecological niche construction" provides a new theoretical perspective for understanding cross-border data governance. Secondly, under the framework of "One Country, Two Systems", the collaborative mechanism of the Guangdong Hong Kong Macao Greater Bay Area is an effective way to break through the fragmentation of data governance rules. The Hetao Cooperation Zone has explored institutional innovation paths and cross-border mutual trust mechanisms through the physical isolation design of "domestic and foreign", the joint governance mechanism between Shenzhen and Hong Kong, and the rule linkage of international standards, which has largely resolved the institutional supply contradiction of "autonomy in norms". Thirdly, the "impossible triangle" of cross-border data flow needs to be gradually resolved in stages, and it is also inseparable from a clear and flexible data security regulatory system. The Hetao Cooperation Zone adopts a dual track approach of "negative list management" and "international rule docking" to reduce risks in the short term through data classification and grading, security assessment, and scenario based pilot projects; In the medium to long term, by sharing computing power and building a trustworthy data space, we promote the compatibility of data sovereignty and circulation efficiency, which provides a progressive reform paradigm of "security first, gradual opening up" for other regions.

This study breaks away from the conventional approach of merely conducting surface - level analyses of policy texts and legal documents. ［15］ Instead, it opts for a micro - perspective to meticulously examine the conditions and innovative practices for establishing offshore data centers and advancing cross - border data services in the Hetao area. This enables a deeper exploration of the ecological niche advantages, disadvantages, experiences of peer cities, and differentiated competition strategies that contribute to the success of cross - border data flows. ［16］ Moreover, this study incorporates the analytical perspective of ecological niche construction theory. By strategically comparing with other cross - border data service centers, it contemplates how to achieve differentiated development, complementary development, opportunistic development, and expansion of the niche width and capacity in the construction of offshore data centers.

In summary, the institutional design and innovative exploration of cross-border data services in the Guangdong Hong Kong Macao Greater Bay Area provide important insights for national data cross-border governance. The pilot experience of the offshore data center in the Hetao Shenzhen-Hong Kong Science and Technology Innovation Cooperation Zone not only provides a practical model for the marketization of global data elements, but also contributes to the "Chinese solution" for global cross-border data governance. How to continuously break through multiple rule constraints and seek more compatible cross-border data flow models, optimize institutional flexibility, and deepen international cooperation in the context of economic globalization will be the core proposition of the next stage.

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Evolution of Spatial-Temporal Pattern and Influencing Factors of Integration of Rural Industrial Integration in China—Based on Data Analysis from China's Four Major Economic Zones

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Abstract: The integration of rural secondary and tertiary industries (referred to as "three - industry integration") is a key pathway to advancing agricultural and rural modernization and an important measure to achieve rural industrial prosperity under the Rural Revitalization Strategy. This study focuses on the level of three - industry integration and its influencing factors in China and its four major economic zones from 2015 to 2024. Using the random effects model and the Oaxaca - Blinder decomposition method for empirical analysis, the study finds that the level of three - industry integration has shown an overall upward trend with fluctuations and exhibits a geographical distribution pattern of "east - west - central" in descending order. From the subsystem perspective, there are significant differences in the development levels of the three - industry integration subsystems across regions, although the overall trend is upward, the development of industrial cycles is relatively slow. Human capital, urbanization, land transfer, and agricultural loans have a significant promoting effect on the integration of the three industries, but they also lead to differences in the level of integrated development across regions to some extent. Based on these findings, it is recommended to continue to focus on the development of rural industrial cycles, guide college students to return to their hometowns to start businesses, promote urbanization and land transfer, to promote high - quality development of the integration of the three rural industries.

Keywords. Rural "Three - Industry" Integration; Evaluation System; Coupling Coordination Degree Model; Oaxaca - Blinder Decomposition Method

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I. Introduction

Since the 19th National Congress of the Communist Party of China, rural industrial integration has achieved remarkable results. However, challenges such as low integration degree, weak technology penetration remain. Effectively promoting rural three-industry integration is crucial for accelerating agricultural modernization and achieving social equity and development. Scholars debate the selection of evaluation indicators[1][2]. Some focus on agricultural industrial chain extension and multi functionality, others on agricultural service integration and economic benefits[3][4]. Some include industrial extension, functional expansion, and urban-rural integration[5][6]. Methods include subjective approaches like the analytic hierarchy process and objective methods like the entropy method[7][8]. Each has pros and cons but aids quantitative analysis.

This paper constructs an evaluation system from four dimensions, uses the coupling coordination degree model to analyze the four major economic zones, and empirically tests influencing factors to provide references for regional rural revitalization and comprehensive rural development.

2. Research Design

2.1 Establishment of Evaluation System and Indicator Composition

Rural "three-industry" integration is a new agricultural organization method and process. It forms new agricultural industries, business forms and models through the integration and penetration, cross-restructuring of various departments within agriculture and between agriculture and rural secondary and tertiary industries. Drawing on relevant studies [9][10], this paper constructs an evaluation system for the level of "three-industry" integration from four dimensions (Table 1).

Table 1 Evaluation System of Rural "Three - Industry" Integration Level

TargetLayer	Subsystem	Indicator Layer	Measurement Method	Data Source
"Three -Industry" Integration	Industrial Extension |	Agricultural Product Processing Industry Scale	Main Business Revenue of Agricultural Product Processing /Total Primary Industry Output	China Agricultural Product Processing Industry Statistical Yearbook |
		Farmers' Professional Cooperatives |Scale	Farmers' Cooperatives Number/ Primary Industry Labor Force Scale	China Farmers Professional Cooperatives Report
	Industrial Intersection	Facility Agriculture Development	Facility AgricultureTotal Area / Crops Total Sowing Area	China Greenhouse Data System
		Development of Agricultural, Forestry, Animal Husbandry and Fishery Service Industry	Output Value of Agricultural, Forestry, Animal Husbandry and Fishery Service Industry / Total Output Value of Primary Industry	China Tertiary Industry Statistical Yearbook
	Industrial Penetration	Agricultural Mechanization Development	Total Power of Agricultural Machinery / Total Sowing Area of Crops	China Rural Statistical Yearbook
		Rural Internet Development	Rural Internet Broadband Access Households Number/ Administrative Villages Total Number	China Tertiary Industry Statistical Yearbook
	Industrial Cycle	Industrial Cycle Utilization of Renewable Resources in Agriculture	Total Gas Production of Biogas Pools / Total Number of Administrative Villages	China Rural Statistical Yearbook
		Use of Agricultural Films	Use of Agricultural Films / Total Sowing Area of Crops	China Rural Statistical Yearbook

2.2 Determination of Evaluation Indicator System Weight

We use the coupling coordination degree model to evaluate "three-industry" integration level and calculate the integration index of various regions from 2015 to 2024.

- Assume i evaluation samples and j evaluation indicators to form a raw indicator data matrix（equation omitted）.
- Normalize the raw indicator data (equations omitted).
- Coupling degree model : $C_n = \left\{(u_1 \times u_2 \times \cdots \times u_n) \div \prod (u_i + u_j)\right\}^{1/n}$ (1)
- Coupling degree model for quaternary system of three industries integration

$$C_4 = \left[\frac{u_1 \times u_2 \times u_3 \times u_4}{\prod u_1 + u_2 + u_3 + u_4}\right]^{1/4} \tag{2}$$

- Coupling coordination degree model is constructed based on the coupling degree to evaluate the interaction between four subsystems.

$$\begin{cases} D = \sqrt{C \times T} \\ T = \alpha f(x) + \beta g(y) + xh(z) + \delta k(w) \end{cases} \tag{3}$$

where D is the coupling coordination degree; C, the coupling degree; T, the comprehensive evaluation value of coupling - coordinated development; and α, β, γ, δ, the subsystem weights.D ranges between 0 and 1. Values closer to 1 indicate better coordinated development, while those near 0 suggest worse coordination. Coordination levels are detailed in Table 2.

Table 2 Classification Criteria for Coupling Coordination Degree

Coordination Level	D	Coordination Degree
1	(0.0,0.1)	Extremely Disordered
2	[0.1,0.2)	Severely Disordered
3	[0.2,0.3)	Moderately Disordered
4	[0.3,0.4)	Slightly Disordered
5	[0.4,0.5)	On the Brink of Disorder
6	[0.5,0.6)	Barely Coordinated
7	[0.6,0.7)	Initially Coordinated
8	[0.7,0.8)	Moderately Coordinated
9	[0.8,0.9)	Well Coordinated
10	[0.9,1.0)	Highly Coordinated

3. Analysis of Rural "Three - Industry" Integration Level

3.1 Data Description

The data excludes the Tibet sample and divides China into four economic regions[2] based on development level. Missing data of some indicators are processed using interpolation methods.

3.2 Overall Analysis

Using evaluation index system and model, three industries integrated development level in 2015-2024 was measured(Table 3). Overall, Integration level increased from 0.1963 in 2015 to 0.8943 in 2024, showing a fluctuating growth trend. Development can be divided into three stages:

- Stable Development (2015–2018): Index rose steadily from 0.1963 in 2015 to 0.6248 in 2018, evolving from severe imbalance to initial coordination.
- Fluctuating Development (2019–2023):Index fluctuated with minimal growth (0.0053 over 2019–2022), remaining at initial coordination, barely reaching coordination in 2021.
- Rapid Development (2023–2024):Index surged from 0.6193 in 2023 to 0.8943 in 2024, advancing from initial to good coordination at a fast pace.

Table 3 The Integrated Development Level of the Three Rural Industries and the Degree of Coupling Coordination in Rural China

	D	Coordination Degree
2015	0.1963	Severely Disordered
2016	0.3749	Slightly Disordered
2017	0.4966	On the Brink of Disorder
2018	0.6248	Initially Coordinated
2019	0.6140	Initially Coordinated
2020	0.6252	Initially Coordinated
2021	0.5808	Barely Coordinated
2022	0.7042	Moderately Coordinated
2023	0.6193	Initially Coordinated
2024	0.8943	Well Coordinated

3.3 Regional Dimension Analysis

From 2015-2024, "three-industry" integration level in various regions increased with fluctuations, and differences between regions gradually narrowed. By 2024, eastern region had the highest level, followed by central, western, and northeastern regions (Table 4).

Reasons include :Eastern Region has a higher marketization degree and developed economy; Central Region has superior geographical location and dense production

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[2]Eastern region: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan; Central region: Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan; Western region: Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang; Northeast region: Liaoning, Jilin, and Heilongjiang.

factors; Western Region benefits from national policies and develops rural industries through leisure agriculture and rural tourism; Northeastern Region has rich land and labor resources and a good agricultural production base.

Table 4 Coupling Coordination Degree of "Three - Industry" Integration in Four Major Economic Zones

	Eastern Region		Central Region		Western Region		Northeastern Region	
	D	**Coordination Level**	**D**	**Coordination Level**	**D**	**Coordination Level**	**D**	**Coordination Level**
2015	0.2545	Moderately Disordered	0.1774	Severely Disordered	0.1933	Severely Disordered	0.2021	Moderately Disordered
2016	0.4319	On the Brink of Disorder	0.2990	Moderately Disordered	0.3401	Slightly Disordered	0.4176	On the Brink of Disorder
2017	0.5445	Barely Coordinated	0.4364	On the Brink of Disorder	0.4555	On the Brink of Disorder	0.4408	On the Brink of Disorder
2018	0.5794	Barely Coordinated	0.5577	Barely Coordinated	0.6493	Initially Coordinated	0.5127	Barely Coordinated
2019	0.6647	Initially Coordinated	0.6181	Initially Coordinated	0.6619	Initially Coordinated	0.6510	Initially Coordinated
2020	0.7378	Moderately Coordinated	0.6043	Initially Coordinated	0.7059	Moderately Coordinated	0.6921	Initially Coordinated
2021	0.5931	Barely Coordinated	0.6426	Initially Coordinated	0.6354	Initially Coordinated	0.6720	Initially Coordinated
2022	0.5371	Barely Coordinated	0.6313	Initially Coordinated	0.7851	Moderately Coordinated	0.5994	Barely Coordinated
2023	0.6485	Initially Coordinated	0.5952	Good Coordinated	0.6171	Initially Coordinated	0.5613	Barely Coordinated
2024	0.9058	High - Quality Coordinated	0.8499	Good Coordinated	0.8653	Good Coordinated	0.8754	Good Coordinated

3.4 Subsystem Dimension Analysis

- Eastern/Central Regions: In 2024, industrial extension and intersection were strong, contributing were prominent. This was due to the inflow of industrial and commercial capital, bringing key factors to rural areas and promoting the development of family farms, modern agricultural parks, and rural processing enterprises. Farmers also established professional cooperatives and formed benefit-sharing mechanisms with agricultural enterprises, building an integrated agricultural industry chain.

- Western Region:A more balanced performance in industrial extension, intersection and penetration, with contributions higher than that of industrial cycle. This was mainly due to rapid economic development and poverty alleviation strategies, which enabled rural industries develop rapidly.Development of ethnic cultural villages and traditional folk skills injected new vitality into industry integration through new business forms.

- Northeastern Region: Performed well in industrial extension and penetration, with contributions higher than those of industrial intersection and cycle. This was due to the good agricultural production base and the broad development space of agricultural product processing industry. By introducing advanced processing and manufacturing technologies, agricultural product processing industry achieved transformation and upgrading, extending industrial chain. However, the rural industrial cycle development level was generally low in all regions.

4. Empirical Analysis of Influencing Factors of the Level of Rural "Three - Industry" Integration

4.1Mechanism Analysis of Influencing Factors of the Level of "Three - Industry" Integration

Human capital is vital for economic growth, enhancing efficiency and innovation, is crucial for rural industrial integration, (Becker, 1962);Urbanization drives economic growth by shifting rural labor to non-agricultural sectors, increasing income and improving infrastructure.(Lewis, 1954);Agricultural Insurance mitigates farming risks, ensuring stable farmer income,aiding industrial integration (Just & Zilberman, 1983);Land Transfer optimizes land use, enabling large-scale farming. (Deininger & Jin, 2005);.Agricultural loans support industrial growth and sustainability by funding infrastructure, tech upgrades, and market expansion, guiding social capital to optimize rural industry structure (Luo & Zhang, 2019).

Analyzing literature, we found that there are mainly five factors affecting three-industry integration:Human Capital (lab),Urbanization Degree (urb), Agricultural Insurance Coverage (ins),Land Transfer Level (land),and Agricultural Loans (loan).

4.2 Model Specification

The F-test, LM-test, and Hausman test results indicate that the random effects model optimally fits this study's data and serves as the benchmark regression model:

$$fusing_{i,t} = \beta_0 + \beta_1 lab_{i,t} + \beta_2 urb_{i,t} + \beta_3 ins_{i,t} + \beta_4 rolt_{i,t} + \beta_5 loan_{i,t} + \varepsilon_{i,t} \tag{4}$$

where $fusing_{ait}$ denotes integration level, i represents region, t signifies year, β_0 is constant term, $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ are the regression coefficients , and ε is random term.

The study highlights significant regional heterogeneity in integration level. To explore the underlying causes, this paper employs the Oaxaca-Blinder counterfactual decomposition method, conducting pairwise regional comparisons.

4.3 Analysis of Influencing Factors of the Level of Rural "Three - Industry" Integration

Based on Table 4, human capital, urbanization, land transfer and agricultural loan have a significant impact on three-industry integration. Human capital, urbanization and land transfer positively impact integration, passing 1% significance test;Agricultural insurance does not pass 1% significance test and has a negative parameter;Agricultural loans pass 5% significance test but have a negative parameter.

Table 5 Test Results of Influencing Factors of Rural "Three - Industry" Integration

Variable	Rural Three - Industry Integration	Standard Deviation	Z	p
Human Capital	**8.9816*****	**2.5401**	**3.5400**	**0.0000**
Urbanization	1.1373***	0.4132	2.7500	0.0006
Agricultural Insurance	-0.1434	0.2881	-0.5000	0.6190
Land Transfer	1.2430***	0.3221	3.8600	0.0000
Agricultural Loans	-0.0160**	0.0076	-2.1000	0.0120
Constant Term	-0.5520**	0.2201	-2.5100	0.0120
R2	0.7552	—	—	—

4.4 Comparison of Influencing Factors of the Level of "Three - Industry" Integration

- Eastern vs. Central Regions:Level difference is mainly due to endowment differences, with agricultural loans being the key factor.
- Eastern vs. Western Regions: Differences are primarily due to endowment differences. Agricultural insurance and land transfer narrow the integration gap, while agricultural loans widen it.
- Eastern vs. Northeastern Regions: Differences are mainly due to endowment differences in human capital and agricultural loans.
- Other Regions: Decomposition coefficients of "endowment differences" for "three-industry" integration among central and northeastern, central and western, and western and northeastern regions are not significant..

Table 6 Oaxaca - Blinder Decomposition Results of Differences in Rural "Three - Industry" Integration

Influencing Factor	Eastern (Benchmark Group) vs. Central		Eastern (Benchmark Group) vs. Western		Eastern (Benchmark Group) vs. Northeastern	
	Endowment Difference	Coefficient Difference	Endowment Difference	Coefficient Difference	Endowment Difference	Coefficient Difference
Human Capita	0.0602	0.1776	0.0550	0.2158	0.1119**	0.1972
Urbanization	-0.7088	-11.4407	-0.1208	-3.4226	-0.1797	-10.1228
Agricultural Insurance	-0.03187	-0.7152	-0.9632***	-1.5177**	0.1512	-1.4844***
Land Transfe	-0.1276	-2.2173**	-0.7911***	-2.4539***	0.3120	-2.7571***
Agricultural Loans	3.0919***	2.7885***	3.0542***	3.2167***	1.9690***	3.0216***
Constant	–	9.4586	–	2.7264	–	8.8086
Overall	1.9970***	-1.9484***	1.2342***	-1.2353***	2.3643***	-2.3370***
Influencing Factor	**Central (Benchmark Group) vs. Western**		**Central (Benchmark Group) vs. Northeastern**		**Western (Benchmark Group) vs. Northeastern**	
	Endowment Difference	Coefficient Difference	Endowment Difference	Coefficient Difference	Endowment Difference	Coefficient Difference
Human Capita	-0.0019	0.0349	0.0290	0.0423	0.0262	0.0122
Urbanization	-3.9795	12.5856	-2.4321	4.2791	-0.2513	-6.5079
Agricultural Insurance	-2.5829	1.1359	0.2669	-0.5663	-11.5217	12.6693*
Land Transfe	-0.3745	-0.5255	0.0579	-0.1582	-1.3923	2.1921
Agricultural Loans	0.0091	0.3814	0.9847*	-1.8745*	2.0498	-3.3302
Constant	–	-6.7322	–	-0.6500	–	6.0821
Overall	-6.9298	6.8801	-1.0935	1.0723	-11.0892	11.1176

5. Research Conclusions and Policy Implications

5.1 Research Conclusions

- "Three-industry" integration exhibits a fluctuating upward trend, reaching a well-coordinated level with relatively rapid development.
- "East-west-central" descending order is observed in the spatial distribution of three-industry integration across regions.
- Significant disparities exist in the development levels of three-industry integration subsystems across regions, yet all show an upward trend. However, the slow development of industrial cycles exerts a "lag effect" on rural industry integration in various regions.

- Key factors like human capital, urbanization, land transfer, agricultural loans greatly affect industry integration, causing regional development differences.

5.2 Policy Recommendations

- Eastern region should establish "Digital Agriculture Fund" and pilot cross-regional land-index trading.
- Western region needs to increase land-transfer policy support with preferential policies and subsidies.
- Support entrepreneurship by Attracting college students to start business.
- Coordinate economic growth, rural labor transfer, urbanization, and urban public facility construction to help rural migrants integrate into cities orderly and effectively.

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Modern Management based on Big Data VI
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Corporate Social Responsibility and Governance Mechanisms of Digital Platforms Facing Technology for Good–A Case Study Based on Meituan Dianping

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Abstract. The boundaries of economic and social attributes of technology-based platform enterprises are more blurred in the platform ecological field, and the paradigm of social responsibility practice and governance mechanism have produced new changes, which require an in-depth analysis of their logic of origin, practice paradigm and governance mechanism. This paper takes Meituan-Dianping, a widely influential technology-based platform enterprise among platform enterprises, as the research object, and explores the definition of its social responsibility in depth to further explore the issue of social responsibility governance mechanism of technology-based platform enterprises. The study finds that the social responsibility of technology-based platform enterprises can be hierarchically divided according to their roles as 'independent operating entities', 'business operation platforms' and 'social resource allocation platforms'. and 'social resources allocation platform'. A contextualized governance mechanism centered on corporate value, a cross-level network governance mechanism, and an iterative ladder governance mechanism are formed to promote the goodness of science and technology.

Keywords. Corporate social responsibility, science and technology platform enterprises, science and technology for good, governance mechanisms

1. Introduction

As mankind moves from the traditional industrial economy to the digital economy, subversive changes in the traditional organizational carriers and business models, and a new type of organizational form represented by technology-based platforms has emerged. Compared with traditional enterprises, technology-based platform enterprises create interactive value and personalized service value by encompassing users, forming a new type of business ecosystem and value co-creation paradigm led by technology-based platforms and linking users and various stakeholders[1].In May 2019, Ma Huateng announced that "technology for the good" has become the new vision and mission of Tencent, and launched a series of event attempts, such as Tencent Youtu based on face recognition technology, joint Fujian Provincial Public Security Department to create "I

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miss you" anti-lost platform, online 14 months to retrieve 681 people [2]. This representative enterprise's typical practice of "science and technology for the good" shows that the selective application of digital technology can present and amplify the process of corporate value orientation and the process of practicing corporate social responsibility.

Various types of technology-based platform enterprises in the digital economy context have differentiated the definition, fulfillment and governance paradigms of CSR in terms of value proposition, creation and delivery to different degrees. Therefore, the content definition, fulfillment mechanism, governance principles and governance paradigms of existing platform CSR are not universally applicable, and should be studied in depth vertically according to the specific differences in the value proposition, creation and delivery of platform enterprises, i.e., based on the enterprise's vision combined with its own resources, competence, value, organization, users, and technological goals.

2. Related Works

How should platform CSR be governed? Scholars at home and abroad have carried out exploratory research and thinking, including defining the scope, object, type and governance mechanism of platform corporate social responsibility in the context of platform economy and many other topics [3-4].CSR practice is a manifestation of the relationship between enterprises and society, a coupling of social issues and enterprise business strategy, and promotes social progress through close integration with the core business activities of enterprises. From the perspective of historical evolution, the concept of CSR has gone through an evolution from narrow CSR to corporate social response, corporate social performance, and then to corporate citizenship.[5]In the digital economy, based on digital technology and Internet platforms, technology-based platform enterprises linking bilateral market users have become a rapidly emerging new organizational form, and there are major differences between the competitive attributes, degree of openness, nature of ownership and other characteristics of traditional enterprises, i.e., technology-based platform enterprise.[6]At present, the research on the social responsibility of technology-based platform enterprises has just started, and some scholars have discussed the basic definition, scope definition, levels and principles of platform enterprises to some extent [7]. Research related to CSR governance practices shows that there are significant differences in the core practice paradigms of searching, embedding and measuring social responsibility between traditional enterprises and technology-based platform enterprises [8]. In the context of the digital economy, corporate social responsibility practices and governance mechanisms have undergone significant changes. It is necessary to trace these changes back to their origins and conduct an in-depth analysis of their underlying logic, practical models, and governance mechanisms.

3. Methods

This study adopts a single case study method to explore the boundaries and connotations of CSR of technology-based platform enterprises in the context of the digital economy, and how to carry out the construction of the mechanism and principles of social responsibility governance, which is a typical "what" and "how" question. It is a typical question of "what" and "how". According to the principle of theoretical sampling, we select cases with great influence and representative cases in China, and analytically summarize from cases to theories through the description and understanding of the cases, as well as grasping the dynamic course and the context of the situation [9].

4. Case Studies

In the era of digital economy, technology-based platform enterprises, represented by Meituan, have gone beyond the boundaries, structure and even market of traditional enterprises, and have become the basic facilities of the overall value creation system. Some scholars suggest that technology-based platform enterprises should break through the traditional enterprise boundaries [10]. Therefore, based on the principle of multi-level division of the subjects of technology-based platform enterprises, this paper, combined with the case study of Meituan Dianping, categorizes the scope of the social responsibility of technology-based platform enterprises, and then defines its connotation in a targeted manner.

4.1. Definition of Social Responsibility as an Independent Operating Entity

Compared with traditional enterprises, technology-based platform enterprises have richer and more innovative social responsibility connotations due to their digital technology attributes. Compared with traditional enterprises in the legal dimension, economic dimension and ethical charity dimension of CSR [11], technology and data have made the connotation boundaries of the social responsibility of technology-based platform enterprises blurrier, more expanded and more efficiency-oriented. Therefore, this paper focuses on the new connotations due to data and technology that are different from traditional corporate CSR when studying technology-based platform enterprises.

- New Meaning of Legal Responsibility

Compared with the clearer and more stable legal environment of traditional enterprises, the rapid change and innovative development of digital technology has blurred the boundaries of the relevant legal provisions, resulting in frequent occurrence of social responsibility alienation. Therefore, before the law perfects the all-round regulation of the application of digital technology, it becomes the proper meaning of the social responsibility of technology-based platform enterprises to consciously maintain the order of the application of digital technology and reduce the occurrence of the alienation of social responsibility. In the face of the relative backwardness of the laws on corporate governance and data rights, Meituan has set up a specialized agency to continuously explore ways to disclose information that take into account publicity and stakeholders' rights and interests, so as to fulfill its corporate legal responsibilities.

- New Concept of Ethical Charitable Responsibility

Ethical philanthropic responsibility is in addition to financial responsibility and the law, with behaviors and activities that may not yet be codified in law but are still expected by society. Compared to traditional forms of charity that revolve around donations and contributions, technology-based platform companies focus on combining their own resources and utilizing the efficiency and relevance of digital technology to fulfill ethical philanthropic responsibilities. Through its platform advantages, Meituan aggregates merchants, consumers, farmers, riders, public welfare organizations and other Meituan ecosystem groups to explore effective paths for accurate poverty alleviation by employment poverty alleviation, training poverty alleviation, consumption poverty alleviation, public welfare poverty alleviation, and tourism poverty alleviation. Boston Consulting Group (BCG) report "Digital Economy Drives Employment" reveals that Meituan Dianping drove 19.6 million labor employment opportunities, and 670,000 people came from impoverished counties out of the 2.7 million distribution employment opportunities, with a considerable A part of them are poor households with national filing cards.

4.2. Defining Social Responsibility as a Commercially Operated Platform

Relying on the interactive trading platform embedded in the business ecosystem, the social responsibility of technology-based platform enterprises should make the operation of the platform ecosystem comply with the social responsibility requirements of all stakeholders from the ecosystem [12] .

- Multilateral Connectivity Responsibilities

When the platform enterprise acts as the leading enterprise in the ecosystem, based on the application of digital science and technology technology, it provides constraint regulation and incentive support for the responsible behavior of the ecosystem members from the supply and demand sides, i.e., the multilateral connectivity responsibility of the technology-based platform enterprise [13]. Technology-based platform enterprises integrate resources based on digital technology and traditional supply chain management, Meituan Dianping establishes a clear procurement process and management system based on traditional supply chain management, connects buyers and sellers to realize accurate value matching, and standardizes the management of the whole procurement process, and Meituan introduces an intelligent scheduling system based on the process of integrating resources based on digital technology to help traditional enterprises be able to respond to the supply and demand of digital economy, and to empower traditional industries. demand, which has an enabling effect on the traditional industry.

- Value Leadership Responsibility

Value proposition is one of the core elements of a business model, and an attractive value proposition can guide an enterprise to build an efficient and stable value chain and external partner network. In the business ecosystem centered on technology-based platform enterprises, the application of digital technology makes the ecological structure more complex, the coordination and cooperation between individual species stronger, and the linkage relationship tighter. Therefore, in order to make the ecosystem evolve as positively as possible, it is necessary for technology-based platform enterprises to play the role of guiding "science and technology for good". On the other hand, in order to advocate that good moral qualities such as "dedication" and "friendliness" have an empowering effect on public welfare projects, Meituan has realized the connection between users and public welfare organizations through the dual combination of the sub-platform of user payment and the public welfare platform, and the buyer's scenario and the interactive interface, and carried out the "Donate with Payment" campaign. The "Donate 1 Yuan for Successful Payment" campaign has fulfilled the responsibility of value leadership.

4.3. Defining social responsibility as a platform for social resource allocation

The multilateral market linked with platform enterprises has given platform enterprises stronger social attributes, while digital technology has given technology-based platform enterprises wider social influence and deeper social embeddedness, which makes the relationship between technology-based platform enterprises and the society more complex, and therefore gives rise to a new ability and scope of social responsibility. The social responsibility assumed by technology-based platform enterprises also requires them to assume the role of "social citizens" from a social perspective, and to gather, allocate and optimize social resources .

- Responsibility for Responsible Innovation

Science and technology innovation is the main driving force to promote the positive evolution of the business ecosystem centered on science and technology-based platform enterprises, and to realize value co-creation and value leadership. Science and technology-based platform enterprises are the most energetic and capable enterprises in the forefront of social science and technology innovation. Meituan-Dianping independently researches and develops the "Electronic Billing System for Merchants Entering the Network" and the "Catering Evaluation Big Data System" oriented on "Responsibility for Cooperative Merchants", through which the social credit, business qualification and user evaluation of catering enterprises are analyzed. By integrating and analyzing data resources such as credit, business qualification and user evaluation of catering enterprises, the system improves the quality of the merchants from the level of resource allocation of the "stationing platform".

- Institutional Prior Responsibility

Science and technology-based platform enterprise science and technology innovation, model innovation, demand innovation of the most energetic subject, the field inherent in the traditional model, relations and habits have a strong subversive, may become the field constantly break the old system, the construction of a new system of institutional entrepreneurs. By timely updating the notification-deletion protection mechanism and deleting and blocking suspected infringing items based on the latest legal provisions as well as complaint materials, Meituan has timely fulfilled the responsibility of institutional entrepreneurship of intellectual property rights protection in advance according to the requirements. Technology-based platform enterprises are not limited to innovating digital technologies and their related applications, but also aim to achieve legitimacy, and on the premise of institutional entrepreneurship risk control, gradually explore, improve and establish new industry systems to fulfill their institutional responsibility.

5. Corporate Social Responsibility Governance Mechanisms for Science and Technology-based Platforms

Corporate social responsibility of science and technology-based platforms has new connotations and characteristics, and good governance of corporate social responsibility can truly realize "science and technology for the good". On the basis of the research on the definition of the content of the social responsibility of science and technology-based platforms, the governance mechanism of their social responsibility can be explored from different dimensions, such as the governance principle of social responsibility, value orientation and coordination and management.

5.1. Contextualized Governance Mechanisms Around Enterprise Value

The value proposition of technology-based platform enterprises is closely related to a series of ways of value creation and value transfer, and different types of technology-based platform enterprises will have strong differences and contexts based on their different value propositions. Based on the governance principle of "doing well for oneself, giving full play to one's strengths and serving the ecosystem", technology-based platform enterprises choose appropriate contexts for social responsibility governance based on their own advantageous resources and on the basis of accomplishing corporate value creation. The social responsibility governance of this corporate value proposition is a contextualized governance mechanism, which has higher requirements for contextual adaptability and comprehensiveness of governance. Therefore, one of the social responsibility governance mechanisms for technology-based platform enterprises is to focus on the enterprise's value, use digital technology as a carrier, take adaptive measures for different application situations corresponding to different subjects in the business ecosystem, and make adjustments, optimizations and innovations during the dynamic evolution of the business ecosystem.

5.2. Cross-level, Networked Governance Mechanisms

For a business ecosystem centered on a technology-based platform enterprise, the system level is more complex, and it is necessary to analyze the linking mechanism between members and the governance mechanism of the same member at different levels, so as to build a multi-party collaborative social responsibility governance paradigm oriented to "better realize value co-creation". In the "supply chain integration" and "species link", Meituan does not fulfill its social responsibility from a single buyer and seller or its own platform level, but rather couples the participants, receptors, governance content and governance mechanism in the ecosphere to form a synergistic social responsibility governance model for each subject and each level. levels of the ecosystem, forming a common governance of social responsibility among all subjects and all levels in collaboration with each other. Therefore, the social responsibility governance mechanism of different types of technology-based platform enterprises should synthesize the social responsibility contents at the platform subject, ecosphere and social environment levels, and aim at "more efficient value co-creation", so as to build a multi-party and multi-level social responsibility co-governance.

5.3. Progressive and Iterative Laddering of Governance Mechanisms

With the diversified development of digital technology applications, technology-based platform enterprises are faced with more and worse incidents of social responsibility alienation and more ambiguous participants. Meituan Dianping App is the core product of Meituan as a technology-based platform enterprise, and user data is the "means of production" for Meituan's value creation. At each level, although Meituan has a plan for the "three steps" of social responsibility governance, the actual results and feedback for improvement are not the same. Therefore, there is a difference in the objectives of social responsibility governance among the three steps corresponding to individual levels, which makes the evaluation model more dynamic.Under the premise that there can be differences in objectives between each level of the “three-step” governance, a systematic, tiered social responsibility governance mechanism should be established from three levels: technology-based platform enterprises, industry ecosystems, and the broader social environment.

6. Conclusions and Outlook

Through the single case analysis of Meituan Dianping, this study defines the content boundaries and connotations of the CSR of technology-based platforms in the context of digital economy, and based on this, it makes a targeted proposal on the principles and mechanisms of the CSR governance of technology-based platform enterprises, and the relevant conclusions are as follows.

First, The social responsibility of technology-based platform enterprises can be divided into three levels based on their roles as “independent operating entities” “commercial operating platforms” and “social resource allocation platforms.” Among these, the social responsibility of “independent operating entities” includes new legal responsibilities and charitable responsibilities; the social responsibility of “commercial operating platforms” includes multilateral linkage responsibilities and value-leading responsibilities; and the social responsibility of “social resource allocation platforms” includes responsible innovation and institutional leadership responsibilities.

Secondly, based on the richer, more complex, and more dynamic nature of new social responsibilities, technology-driven platform companies have developed social responsibility governance mechanisms that align with these new responsibilities. By focusing on the value of the enterprise, using digital technology as a carrier, and taking adaptive measures for different application scenarios corresponding to different entities in the business ecosystem, and adjusting, optimizing, and innovating in the dynamic evolution of the business ecosystem, a systematic social responsibility governance mechanism based on “minimum requirements” “reasonable expectations” and “contribution advantages” is constructed at three levels: technology-based platform enterprises, industry ecosystems, and the broader social environment.

Thirdly, this paper still has some shortcomings, such as the external validity of a single case study is relatively low and the lack of clear practical guidance or step-by-step procedures, and the failure to specify measurable indicators or evaluation methods. In future research, we will develop specific evaluation frameworks and quantitative indicators for the corporate social responsibility performance of technology platforms to facilitate empirical testing and practical application, thereby enhancing the contribution and influence of this research.

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Research on H Enterprise Equity Incentive's Questions and Countermeasures

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Abstract. Equity incentives, as a key long-term incentive mechanism, are of great significance in solving the prevalent principal-agent problem. This paper takes Enterprise H as the case study object and utilizes the exploratory case study method to explore it in depth. Firstly, we briefly introduce Enterprise H and its shareholding structure, and then analyze the current situation of the implementation of equity incentives in Enterprise H. From the definition of the scope of the incentive target and the setting of the assessment indexes, we present an all-round compendium. Accordingly, the main problems of equity incentives in Enterprise H are summarized, such as the coverage of incentive targets is too small, the performance assessment indexes are defective, and the fixed exercise price is not scientific, etc. Digging deeper into the root cause, it may be due to the lack of science in the internal control mechanism of the enterprise, the market of professional managers is not yet perfect, and the external market environment is still not yet mature and other factors. In the end, for the problems and causes, put forward the corresponding perfect countermeasures, this study not only adds personalized cases for the academic field of equity incentives, enriching the research connotation, but also provides valuable reference for the implementation of equity incentives for China's listed companies, helping them to build a scientific and efficient incentive system, and promoting the sustainable development of the enterprise and the enhancement of its value.

Keywords. Equity incentive; Principal-agent theory; Listed company

1. Introduction

Pfizer Pharmaceuticals first designed and launched an equity incentive program in the 1950s for the purpose of reasonable tax avoidance, and then introduced it into the European capitalist market in the mid-1970s, and it was widely used in Japan in the 1990s. Equity incentive system in the 21st century in China began to sprout development, China has introduced a new securities law, company law and a series of laws and regulations to promote the standardization of China's equity incentive system and the development of the legal system.

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The purpose of implementing equity incentives is mainly to attract high-quality talents for the company, retain core employees and effectively promote the improvement of the company's performance, etc. In China, after 2005, more and more companies have begun to launch different equity incentive programs to achieve the above purposes, through the adoption of incentive policies suitable for the company's development strategy to improve the corporate governance structure, enhance the stickiness of core talents, and achieve sustainable development. However, from the previous literature, China's listed companies for the implementation of equity incentives is still in the exploratory stage, many enterprises designed by the equity incentive program there are still shortcomings, thus leading to many enterprises in the implementation of equity incentives encountered a variety of problems, which makes the incentive plan failure. At the same time, in real life, most of the enterprises' equity incentive programs still have many deficiencies, this paper begins to H enterprise as the object of study for case study, in order to provide researchers with relevant practical case support.

2. Related works

Since Berle and Means proposed that equity incentives can bind the interests of managers and owners in 1932, related research has been deepening both at home and abroad, and Jensen and Meckling's "interest convergence hypothesis" emphasizes that equity incentives can make the interests of management and shareholders converge, thus reducing agency costs and improving firm performance [1]. Fama further pointed out that equity incentives can alleviate the conflicts between owners and operators due to the separation of rights. However, the conclusions of foreign scholars on the effects of equity incentives are divergent: most studies believe that equity incentives are conducive to enhancing the performance of listed companies, such as Morgan [2] and other empirical analyses from a variety of perspectives; some studies point out that equity incentives may bring negative impacts, for example, Fama and Jensen [3] mention that the management obtains greater power due to equity incentives but lacks effective supervision; and some scholars put forward the "interval effect", for example, Griffith et al. find that there is a curvilinear correlation between CEO's shareholding ratio and the performance of U.S. commercial bank but it is difficult to determine the optimal interval. In general, foreign research centers on the convergence of the interests of managers and owners, and the incentive effect focuses on the impact of performance, although there are more in-depth discussions on theory and empirical evidence, but the differences in the effects of equity incentives in different industries, different enterprise sizes and different market environments are not enough, and there is a lack of more targeted and detailed research.

Domestic equity incentive research presents a multidimensional trend. In terms of theoretical research, Sun Yumei [4] pointed out that equity incentives are the innovation of the internal distribution system of enterprises, which is in the primary stage in China. The Fourth Plenary Session of the Fifteenth Central Committee of the Party proposed that equity incentives can be tried on a small number of enterprise managers, and it is necessary to continue to explore and summarize the experience to avoid excessive. In terms of effectiveness research, there are a variety of views on the impact of equity incentives on company performance: Xiao Shufang and Fu Wei, Zhang Nan, etc. confirmed the favorable impact of equity incentives on company performance through empirical research [5]; Li Xinjian and others believe that the relationship between compensation, equity incentives and shareholders' equity is an inverted U-shape, i.e., within a certain range, equity incentives can enhance company performance, but beyond a certain threshold, the incentive effect will be weaken [6]; Wang Qiuxia et al. found that in some cases, equity incentives may have a negative impact on firm performance [7]; some scholars believe that there is a non-linear relationship between equity incentives and firm performance, i.e., the effect of equity incentives may be very different in different contexts. In addition, Hua Yuxin argues that the relationship between equity incentives and corporate governance is uncertain [8], and Luo Exiang finds that executive equity incentives play different roles in state-owned and non-state-owned high-tech enterprises [9]. Although domestic research enriches the theory and practice of equity incentives from multiple perspectives, there are fewer in-depth analyses of a single case and a lack of in-depth analysis of the practice of equity incentives in specific enterprises, which is not conducive to the close integration and mutual promotion of theory and practice. Generally speaking, domestic research focuses on both theory and effect, and although multiple perspectives enrich the theory and effect, the research focuses on the impact of performance and other indicators, and less in-depth analysis of a single case, therefore, this paper selects representative listed companies to conduct a case study in order to explore the practical application of equity incentives in the enterprise and the internal logic.

3. Methods

The purpose of this paper is to explore the existing problems and coping strategies of equity incentives in H enterprise. In view of the dynamics of the research background and the complexity of the problem, the exploratory case study method is adopted to describe the research phenomenon in detail and analyze it in depth, so as to reveal the theoretical law behind it. This method is chosen because it is a comprehensive research strategy, focusing on the "how" of the problem through analysis and generalization, and is conducive to the exploration of the process and evolutionary mechanism, so as to extract the developmental laws from the qualitative data, analyze the theoretical links behind the complex phenomenon, accurately summarize the characteristics of the phenomenon, and deepen the overall understanding of the phenomenon.

3.1 Case firm selection

In this paper, Enterprise H is selected as a case study for two reasons. First, it is in line with the requirements of typical case selection. The practice of Enterprise H in equity incentives, covering plan development, implementation and impact, is closely related to the research topic and can provide sufficient material. Secondly, it follows the principle of inspiration, as its experience of equity incentive is of great reference value to its peers and similar enterprises, which can help them optimize the mechanism, prevent risks, and make scientific decision-making and planning.

3.2 Characterisation and shareholder structure of company H

H Enterprise, founded in 1984 and listed on A-share of Shanghai Stock Exchange in 1993, is a smart home eco-brand merchant headquartered in Qingdao. It centers on "white home appliances", creates smart life experiences with diverse combinations to meet user needs. Upholding the user experience concept, it has transformed via entrepreneurship and innovation, becoming a smart home leader. In terms of shareholding, H Group, the de facto controller, directly and indirectly holds around 26% of the shares. The proportion is low, the first major shareholder is relatively powerful, the structure is fragmented, leading to redundant costs, prominent issues in industrial chain operational efficiency, and emerging problems in the balance of interests and management.

4. Analysis of the current situation of the implementation of equity incentives in Enterprise H

4.1 Stock option model related to equity incentives

Enterprise H's equity incentives were shelved in 2006 due to exceeding the SEC(US Securities and Exchange Commission)'s standards, and then restarted and pushed the draft in 2009, and then announced and implemented the second to fifth phases of the plan in 2010, 2012, 2014, and 2022 successively, except for the fourth phase, which has two modes, and most of them adopt the stock option mode, as detailed in the table of comparison of the plans of each phase.

Table 1. Specifics of equity incentive stock options by period

Period	Incentive Model	Stock Source	Incentive Recipients	Type of Incentive Recipients	Grant Scale	Grant Proportion	Validity Period	Grant Price
First Phase	Stock Options	Private Placement	49 Individuals	Corporate Directors, Senior Management, Core Technical Personnel	17.71 Million Shares	1.323% of Total Share Capital	5 Years	10.88 Yuan/Share
Second Phase	Stock Options	Private Placement	83 Individuals	Senior Management, Business Key Personnel	10.8 Million Shares	0.807% of Total Share Capital	4 Years	22.31 Yuan/Share
Third Phase	Stock Options	Private Placement	222 Individuals	All Core Technical Personnel	26 Million Shares	0.97% of Total Share Capital	3 Years	11.36 Yuan/Share
Fourth Phase	Stock Options	Private Placement	455 Individuals	Corporate Directors, Senior Management, Core Technical Personnel	47.64 Million Shares	1.75% of Total Share Capital	4 Years	17.09 Yuan/Share
Fifth Phase	Stock Options	Private Placement	1,840 Individuals	Company Business Supervisors, Core Technical Personnel, Business Key Personnel	105.152 Million Shares	1.11% of Total Share Capital	5 Years	23.86 Yuan/Share

Source: Summary of Enterprise H's (Draft) Stock Option Incentive Plan by Phase

Table 2. Exercise results of equity incentive stock options for each period

Period	Vesting Phase	Exercise Price	Exercisable Individuals	Exercisable Quantity (in 10,000s)
First Phase	First	10.58	41	144.3
	Second	5.24	40	520.4
	Third	5.07	36	718.44
	Fourth	4.7	36	971.04
Second Phase	First	10.94	70	144.3
	Second	10.57	68	520.4
	Third	10.11	68	718.44
Third Phase	First	10.82	200	1078.2
	Second	10.36	196	1122.6
Fourth Phase	First	10.36	423	3090.4
	Second	16.63	412	2560.74

Source: Summary of Enterprise H's (Draft) Stock Option Incentive Plan by Phase

Table 3. Achievement of equity incentive performance targets by period

Period	Year	Performance Evaluation Indicator	Predetermined Target Value	Actual Completion Value	Completion Status (Yes/No)
First Phase	2009	Weighted Average Return on Net Assets After Deducting Non-recurring Profit and Loss	Not Less Than 10%	14.70%	Yes
	2010			25.42%	Yes
	2011			29.96%	Yes
	2012			32.83%	Yes
	2009	Compound Annual Growth Rate of Net Profit (Compared to 2008)	Not Less Than 18%	38.93%	Yes
	2010			54.31%	Yes
	2011			46.96%	Yes
	2012			42.61%	Yes
Second Phase	2010	Weighted Average Return on Net Assets After Deducting Non-recurring Profit and Loss	Not Less Than 10%	25.42%	Yes
	2011			29.96%	Yes
	2012			32.83%	Yes
	2010	Compound Annual Growth Rate of Net Profit (Compared to 2009)	Not Less Than 18%	50.32%	Yes
	2011			39.33%	Yes
	2012			32.40%	Yes
Third Phase	2012	Weighted Average Return on Net Assets After Deducting Non-recurring Profit and Loss	Not Less Than 10%	32.83%	Yes
	2013			29.62%	Yes
	2012	Compound Annual Growth Rate of Net Profit (Compared to 2011)	Not Less Than 12%	30.31%	Yes
	2013		Not Less Than 28.80%	54.18%	Yes

Fourth Phase	2014	Weighted Average Return on Net Assets After Deducting Non-recurring Profit and Loss	Not Less Than 20%	23.89%	Yes
	2015			13.86%	No
	2014	Compound Annual Growth Rate of Net Profit (Compared to 2013)	Not Less Than 15%	20.36%	Yes
	2015			3.20%	No
Fifth Phase	2022	Net Profit Attributable to Shareholders of the Parent Company	Not Less Than 15%	12.58%	No
	2023			13.30%	No
	2024			Unknown data	
	2025				

Source: Enterprise H annual reports

4.2 Restricted stock model related to equity incentives

Enterprise H in the fourth phase of the equity incentive restricted stock the company intends to grant 6,920,000 shares of the company's restricted stock to the incentive recipients, accounting for 0.25% of the company's total share capital, the restricted stock of the annual performance evaluation performance indicators are the same as the above mentioned during the same period of the stock options, the grant price of $ 8.19 per share, the validity of the period for four years.

5. Results and Discussion

5.1 Major Problems of Equity Incentives in Enterprise H

The equity incentive program of Enterprise H has various defects, mainly reflected in the scope of incentive targets, the assessment index system and the determination of exercise price, which have a negative impact on its long-term development. First of all, in terms of incentive targets, the scope of coverage of Enterprise H's equity incentive program is too narrow, focusing only on middle and senior management and core technical staff and other veteran employees, while many new technical staff, grassroots and front-line employees are excluded. This design leads to a lack of incentives for new employees, which may dampen their enthusiasm for work and lead to hidden management problems, thus hindering the long-term development of the enterprise. Secondly, in terms of assessment indicators, the equity incentive program of Enterprise H only adopts two financial indicators, namely, return on net assets and net profit growth rate, which is difficult to fit the original intention of driving incentive recipients to undertake the long-term development of strategic objectives. This single assessment index system cannot effectively assess and accurately predict the long-term development effectiveness of the enterprise, and is likely to give rise to short-sighted behavior of the incentive recipients. For example, the 2022 Incentive Plan only uses the net profit growth rate as the condition for exercising the right, and does not include the indicators in the balance sheet. This single assessment index system not only fails to reflect the long-term development capability of the enterprise, but is also easy to be manipulated by executives through surplus management and other means, thus failing to effectively incentivize the commercialization of innovative products. Finally, in terms of the determination of exercise price, the fixed exercise price of Enterprise H lacks scientific nature, and its determination process is affected by a variety of uncertain and subjective factors, such as market supply and demand, the actual value of assets, and the expected trend. This unreasonable exercise price setting may lead to unreasonable option contracts, making it difficult for employees to accurately predict the market trend, which in turn affects the incentive effect. For example, in the 2022 Incentive Plan, the determination of the exercise price is mainly based on the average price of stock trading before the announcement without fully considering the market fluctuation and the long-term value of the enterprise. In addition, the validity period of Enterprise H's equity incentive plan is relatively short, usually 3-5 years, making it difficult to meet the long-term incentives required for the commercialization of innovative products.

5.2 Analysis of the Reasons for the Major Problems of Equity Incentives in Enterprise H

Equity incentives in Enterprise H face multiple difficulties. In terms of internal control mechanism, the grantors and recipients are mostly middle and senior managers, presenting the characteristics of "self-production and self-sale", especially significant in the early stage of the plan. This mechanism lacks fairness and scientificity, and there is much room for manipulation, which is easy to lead to the phenomenon of personal gain at the expense of the public. It is difficult to exclude subjective interference in the self-supervision and assessment of the grantee. Given that the interests of the operator and the owner are not completely consistent, the management may use the mechanism of fixing the exercise price to seek short-term benefits to the detriment of the company's long-term earnings, resulting in employee motivation is frustrated, and it is difficult to achieve the company's long-term goals. The market for professional managers is also imperfect, with the market mechanism, degree of competition and recruitment efficiency all needing to be improved. Information transparency is low, recruitment information and standards are not publicized, salary levels are unclear, job seekers have difficulty in accessing recruitment channels and salary expectations are not in line with reality. At the same time, the differences in corporate culture make the enterprises' demand for talents and recruitment standards different, which makes it difficult to match the appropriate excellent professional managers, and then makes the performance assessment indexes formulated single, fail to synergize with the company's strategic objectives and values, and lack of scientificity and reasonableness. In addition, the external market environment is not mature enough, the laws and regulations related to equity incentives are not yet perfect, and the market environment is complex and volatile. Taking Enterprise H as an example, as an enterprise that implemented equity incentives at an early stage, although it has achieved certain results at the initial stage, the long-term incentive effect and the promotion of the company's long-term development have not met the expectations, and it still needs to be continuously optimized and improved.

5.3 Countermeasures to Improve Equity Incentives in Enterprise H

Problems with equity incentives in Enterprise H have arisen frequently, and there is an urgent need to improve the strategy to reduce the agency cost. From the perspective of principal-agent theory, expanding the scope of incentives to include grassroots and new employees can reduce information asymmetry, lower the "moral hazard" and "adverse selection" behavior of employees, and bind more employees' interests to the company's interests, thus reducing agency costs. At the same time, a sound appraisal index system and the introduction of non-financial indicators can more comprehensively assess the contribution of employees, avoid the short-sighted behavior caused by a single financial indicator, and motivate employees to work hard for the long-term development of the enterprise. In addition, optimizing the exercise price and introducing a flexible mechanism can make the exercise price reflect the company's value more scientifically and reasonably, and reduce the agency cost caused by unreasonable exercise price. Completing the professional manager market, by establishing an information platform, optimizing the recruitment process, and strengthening industry supervision, can promote the rationalization of manager selection, improve the correlation between managers' market value and performance, and motivate them to work harder. Finally, building a sound external market environment, improving regulations, sound mechanisms, optimizing taxes, and stimulating market vitality can enhance market transparency and fairness, and safeguard the sustainable and healthy development of enterprises.

5.4 The future research directions

This study provides an in-depth analysis of Enterprise H's equity incentive plan and employee stock ownership plan, but due to the difficulty in gaining in-depth knowledge of the case company's internal information, the references and data are mainly based on the relevant announcements and other publicly available data, resulting in insufficient in-depth analysis of the specific details of the incentive plan. For example, the announcement did not clearly state the assessment method at the individual level, making it impossible to determine the reasonableness of the assessment conditions at the individual level. In addition, due to the author's limited expertise, it is difficult to comprehensively assess the effectiveness of the equity incentives by only looking at the company's annual report and official website to understand the company's financial and personnel adjustments and development planning, and without in-depth communication with the company's employees. Meanwhile, the conclusions and recommendations based on the case study of Enterprise H may not be fully applicable to other industries or enterprises in the same industry. Accordingly, future research should expand the information collection channels, increase the range of case companies, and further assess the effectiveness of corporate equity incentives in order to better provide reasonable, comprehensive, and targeted recommendations for the implementation of equity incentive program design and management decisions.

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Mechanisms and Pathways for the Integration of Museum Immersive Experiences with "Great Ideological and Political Course": Based on the Interaction Ritual Chains Theory

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Abstract. Traditional museum visitation is evolving from passive observation to technology-driven immersive engagement. This transformation bridges the gap between audiences and cultural artifacts, unleashing the cultural value of artifacts while amplifying museums' ideological education potential. Through the lens of interactive ritual chains, this study identifies emotional engagement as the critical catalyst for integrating museum immersion with ideological education. The research reveals a three-phase integration mechanism: emotional input through multi-sensory stimulation, physical participation via interactive technologies, and emotional resonance through shared symbolic experiences. We propose a co-creation framework emphasizing collective consciousness-building, emotional alignment, and symbolic meaning-making to optimize museums' role in contemporary ideological education. Additionally, by taking the "Yunyou Dunhuang" as a case study, this research analyzes the feasibility of integrating museum immersive experiences with "Great Ideological and Political Course", offering theoretical insights to transcend the limitations of traditional ideological education.

Keywords. Interactive ritual chain; Museum; Immersive experiences; Ideological education

1. Introduction

On March 6, 2021, General Secretary Xi Jinping first proposed the concept of "Great Ideological and Political Course" (GIPC), stressing its integration with real-world contexts. Over the past decade, General Secretary Xi Jinping has emphasized the critical role of museums in multiple addresses, stating that "every museum serves as a vital educational institution" and urging "innovative use of digital technologies to narrate and disseminate the historical narratives embedded in cultural artifacts". As

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President Xi noted, they are “schools for all” where technology can unlock and share the stories behind artifacts. Museums function as vital platforms connecting the “ideological-political education system” with “social learning spaces” [1] inherently embedded with rich political-educational dimensions.

In the digital-intelligence era, museum immersive experiences marked by highly interactive engagement and experiential focus are accelerating the museum paradigm's shift from object-centric curation to visitor-centered pedagogy. This paper proposes a human-centered framework to integrate museum immersive experiences with “Great Ideological and Political Course” (GIPC). Utilizing the interactive ritual chain, leveraging interactive ritual chains through affective storytelling and embodied interactions, it builds museum-education synergy to amplify cultural identity formation.

2. Literature Review

2.1. Exploration of the interaction ritual chain theory perspective

Goffman introduced the term interaction ritual based on Durkheim’s research[2][3]. This theoretical originated with an emphasis on the conceptualization of rituals and their social functions. Expanding upon this foundation, Collins delineated the operational mechanisms of interaction rituals, employing micro-sociological analysis to explicate phenomena including social solidarity, conflict dynamics, and collective transformation[4].Collins identified four essential components for sustaining interaction rituals: group solidarity, individual emotional energy, symbols representing the group, and a sense of morality[4].This theory has been applied across various contexts, including brand image perception[5], service design optimization[6], leisure experiences[7] and religious participation[8]. The core idea is that repeated social interactions, when structured as rituals, can create a chain of emotional and social outcomes that influence individual and group behaviors.

2.2. Relevant Research of Museum Immersive Experiences

Modern museums increasingly rely on immersive technologies like VR and AR to create interactive educational environments that go beyond traditional displays. These tools boost visitor engagement, learning, and satisfaction while tackling challenges like authenticity and sensory overload. Key aspects are summarized as follows.

In the area of impact on visitor engagement and learning, Immersive technologies, significantly enhance visitor engagement by providing interactive and multisensory experiences. These technologies allow visitors to explore exhibits in a more engaging manner, leading to increased satisfaction and revisit intentions[9][10].The use of sound in VR enhances presence and attention, improving learning outcomes[11].

In the area of educational and cultural implications, Immersive-museum experiences can serve as powerful educational tools fostering understanding and cultural awareness via polyvocal narratives (e.g., VR exhibitions)[12].The integration of deep learning and multimedia technologies enriching visitor experiences, providing more precise and comprehensive displays and interpretations of exhibits[13].

Despite benefits, immersive experiences in museums also present challenges that need to be addressed to maximize their effectiveness. Museums must carefully design these experiences to ensure they complement traditional exhibits and provide authentic, engaging, and educational environments. Balancing technological innovation with cultural and educational goals is crucial for the sustainable development of immersive museum experiences.

2.3. Relevant Research of "Great Ideological and Political Course"

The "Great Ideological-Political Course" (GIPC) advocates moving beyond traditional classrooms by integrating societal resources and practical contexts, building an educational framework of universal engagement, lifelong learning, and cross-domain integration.

In the area of technological integration in ideological and political Education, AI personalizes learning in ideological courses. For example, AI-driven models like the artificial multi-verse optimizer (AMVO) have been developed to predict and boost course effectiveness by analyzing student data[14].

In the area of impact on student development, the use of intelligent educational technologies has been shown to enhance students' comprehensive quality, including their moral and ideological development. This is achieved through personalized educational resources and the continuous evaluation of student progress[15].

While the integration of technology in ideological and political education offers numerous benefits, it also presents challenges. The effectiveness of these technologies depends on their proper implementation and the ability of educators to adapt to new teaching paradigms. Despite these challenges, the ongoing research and development in this field suggest a promising future for the enhancement of ideological and political education through technological innovation.

3. Forms and Characteristics of Museum Immersive Experiences

3.1. Constructing Digital Collectives: Achieving "Spatial Transcendence"

The widespread adoption of immersive technologies has expanded traditional museum visits into online platforms. During COVID-19, when physical access was restricted, museums turned to digital solutions as essential tools for cultural engagement. By digitizing historical artifacts and aggregating collection data, institutions now create app-based virtual environments that transcend geographical barriers. Visitors log in remotely, achieving "virtual presence" through personal devices.

3.2. Demarcating Interactional Boundaries: Curating Focused Ritual Spaces

Establishing participant boundaries is critical for enhancing group belonging and sustaining interaction intensity in museum immersive experiences.User and technological factors generate three boundary types. Closed-Group Access require participants to meet strict criteria, such as verified identity paired with exclusive qualifications or specialized hardware. Semi-Closed Collaboration operates through partnerships with external organizations (e.g., schools or corporate entities), granting access to predefined groups after identity verification. Open-Access Participation accessible via physical installations or web platforms (e.g., online VR galleries).

3.3. Crafting Narrative Immersion: Anchoring Collective Attention

Shared focus is key to engaging museum visitors. Museums design stories and programs to direct attention to cultural-historical themes. While personal views differ, this builds shared understanding and group unity–reflecting interaction rituals' core principle. Multi-sensory layers (spatial audio, touch feedback) reinforce core messages, creating unified story worlds that keep attention anchored.

3.4. Engineering Multidimensional Engagement: Facilitating Affective Exchange

It is believed that emotional energy as used by Collins is, essentially, "energy activation" [16]. It drives museums to integrate multisensory technologies: 3D visuals, spatial audio, and touch interfaces create immersive presence, while smells or tastes deepen emotional connections. Interactive tools–like gesture controls, motion-triggered stories, and facial expression animations–turn passive viewing into collaborative storytelling. These interactions build shared emotional moments: laughter in VR groups or collective awe during historical scenes. By linking sensory inputs with responsive systems, museums create feedback loops that boost learning and foster emotional bonds through participation.

4. The Convergent Logic of Museum Immersive Experiences within "GIPC"

4.1. Innovating Pedagogical Models to Expand the Spatiotemporal Scope of "GIPC"

Museum digital technologies break time-space limits of traditional civic education, extending ideological learning from classrooms to society. Pedagogy shifts from lectures to participatory co-creation. Immersive experiences align with digital-native learners' multisensory preferences, countering conventional monotony. This innovation revitalizes engagement with cultural-ideological content and boosts civic education through tech-mediated experiential history learning.

4.2. Narrative Innovation: Deepening "GIPC" through Multimodal Storytelling

Museums' cultural artifacts and wisdom offer rich material to refresh civic education narratives. Addressing digital-native learners' preference for emotional resonance over lectures, technologies like digital twins and holography convert abstract ideologies into visceral learning. Holographic reenactments of historical moments, for instance, let students witness ideological struggles through personalized lenses. This shift from monologic to polyphonic engagement transforms cultural resources into dynamic pedagogical tools, aligning with Gen Z's cognitive styles while sustaining ideological education's digital relevance.

4.3. Resource Expansion: Enhancing "GIPC" through Curricular Instructional

Enhancing "GIPC" advances through two pathways: curricular enrichment and educator diversification. Museums' immersive tech converts static content into interactive school modules, boosting engagement and value internalization. Museum-school collaborations engage professionals as co-educators, Professionals co-teach via immersive tech, bridging theory and cultural practice. Merging museum tech with pedagogy scales education quality while preserving authenticity−shifting from knowledge transfer to value cultivation.

5. Developing Interaction Mechanisms Between "GIPC" and Museum Immersive Experiences

5.1. Emotional Anchoring: Core Ideological Elements via Museum Immersion

Museum immersion cultivates socio-emotional skills while delivering ideological messaging. Starting with emotional priming, education progresses via resonance. VR/AR-reconstructed contexts and symbolic interactions deepen exhibit engagement. Strategic empathy triggers and emotional cues enhance "social presence" −a shared state fostering collective ideological absorption. This transforms abstract politics into visceral experiences, amplifying cultural value recognition.

5.2. Embodied Action: From Ideological Identification to Practice via Immersion

Museums use physical interaction and sensory engagement to activate neurological responses, aligning visitors with ideological content. Interactive rituals show synchronized actions boost focus and emotional connection. Immersive technologies enable physical-mental internalization of concepts. Tactile interfaces transform abstract ideas into tangible practices, promoting daily embodiment of socialist values.

5.3. Affective Symbols: Museum Immersive Experiences building Cultural Identity

Museum immersive technologies foster ideological-cultural belonging through affectively charged participatory rituals. By situating visitors in VR/AR-enhanced historical environments these experiences convert abstract political narratives into visceral bodily engagements. Cyclical activities trigger collective dopamine cycles, converting fleeting emotions into lasting cognitive schemas. Crucially, user-generated content as shareable symbolic tokens, enabling peer-driven dissemination of civic values across digital platforms. This ritualized ecosystem leverages technological mediation to anchor ideological discourse in embodied cultural literacy.

6. Operationalizing a Convergence Pathway: Embedding Museum Immersive Technologies in "GIPC"

6.1. Situational Engineering: Activating Shared Consciousness

Collins posits that aligned consciousness enables symbolic communication of internal states. Immersive museums construct narrative ecosystems that merge exhibition themes with spatial storytelling—digitally resurrecting historical epochs or simulating future scenarios. By transmuting static textbook knowledge into lived environments, passive learning shifts to active discovery. Such scenographic interventions subtly integrate societal "macro-classroom" resources into ideological "micro-classrooms," deepening value internalization through experiential historiography.

6.2. Affective Amplification: Intensifying Emotional Cohesion

Post-situational priming, emotional intensity requires structured reinforcement. Multisensory interactives—tactile interfaces, VR reenactments—elevate affective investment while transcending resource barriers. For instance, VR simulations of pivotal historical moments synchronize group emotional peaks, transforming individual experiences into collective epiphanies. This layered engagement amplifies ideological messaging's penetrative power, fostering durable group allegiance.

6.3. Symbolic Codification: Perpetuating Ideological Internalization

Ritual-generated symbols sustain collective fervor beyond immediate experiences. Post-visit, participants exhibit heightened sharing impulses—leveraged through digital-social integrations (e.g., gamified learning modules) that extend symbolic recall. Collaborative pedagogic resources (museum-school hybrid courses) bridge academic and societal domains[17], embedding immersive narratives into daily practice. These strategies convert transient emotional energy into lifelong ideological praxis—patriotism, civic duty—manifested through habitual behaviors.

7. Case Study of the Digital Online Museum "Yunyou Dunhuang"

7.1. Case Overview of the "Yunyou Dunhuang"

Currently, the development of immersive experiences in Chinese museums has entered a new phase of innovative advancement, primarily manifested in two distinct modes: creating virtual replicas through digital imaging and processing of museum artifacts for online exhibitions, and delivering on-site immersive displays via dedicated immersive halls or temporary exhibits.This study focuses on Yunyou Dunhuang, a pioneering mini-program integrating exploration, virtual tours, and preservation of Dunhuang Grotto art. By October 2024, it attracted over 200 million users, solidifying its role as a key platform for promoting Dunhuang culture and global heritage conservation.

7.2. The "Yunyou Dunhuang" and Interaction Ritual Chains

This section analyzes the "Yunyou Dunhuang" program through the lens of interaction ritual chain theory, integrating its operational mechanisms into the platform's experiential scenarios. It examines the program's immersive experience model (Figure 2) across three dimensions: ritual construction, ritual performance, and ritual outcomes.

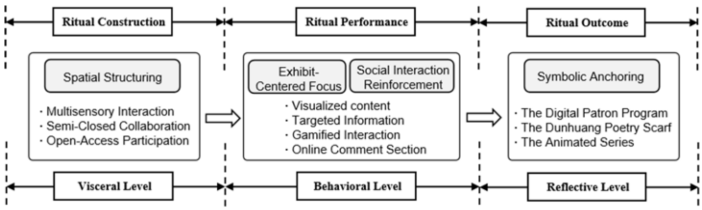

Figure 1 Immersive Experience Model of the 'Dunhuang Virtual Tour' Based on Interaction Ritual Chains

- Achieving "Virtual Bodily Co-Presence" via the Mini Program

The "Yunyou Dunhuang" establishes a digital community where users from diverse locations interact through shared virtual spaces. This enables "technologically mediated bodily co-presence," allowing participants to manipulate avatars and view mural details on mobile devices. Real-time comments and interactions further create synchronized, embodied engagement, fostering a collective sense of presence.

- "Dual Constraints" Enhance Emotional Energy

The program employs semi-closed and open modes to enhance engagement. Semi-Closed Collaboration (e.g., cultural courses, poetry explorations) require reservations for personalized experiences. Open-Access Participation offers barrier-free access to features like "Daily Cave" recommendations and thematic explorations by era, color, or art style. This dual structure strengthens core users' cultural identity while attracting new participants, boosting emotional energy accumulation.

- "Focus on Exhibits" to Evoke Emotional Resonance

Using VR, AR, and 3D modeling, the program sustains attention on Dunhuang artifacts through: Firstly, Visualized content: Categorized exhibits with multimedia guides (images, videos, audio).Secondly, Algorithm-driven "Today's Story" highlighting murals linked to seasons/events. Thirdly, Gamified interaction: Activities like voice-dubbing animations deepen engagement. All strategies prioritize exhibits, guiding users toward focused exploration and emotional connection.

- "Multi-Dimensional Interaction" for Emotional Sharing

The program fosters shared emotional experiences through multi-dimensional interactions, integrating immersive sensory engagement via ancient music and panoramic murals that activate sight and sound, alongside emotionally-driven projects such as the Digital Patron Program (enabling symbolic donations for virtual "guardian" roles), the Dunhuang Poetry Scarf (allowing users to create and share customizable designs). By merging human interactions with cultural artifacts, these layered engagements form a sustainable emotional network.

7.3. Analysis of Ritual Efficacy Based on "Yunyou Dunhuang"

This study applies grounded theory to analyze the ritual efficacy of museum immersive experiences from the audience perspective, focusing on Yunyou Dunhuang users. The mini-program' s built-in comment section serves as a key channel for real-time feedback, while Xiaohongshu has become a key space for youth experience-sharing. Both platforms provide insights into youth perceptions, emotions, and behaviors. Data from Yunyou Dunhuang comments and Xiaohongshu posts (2020-April 2025) were collected. After data cleansing, 212 Xiaohongshu posts and 1,323 textual comments were retained, forming the raw dataset for three-level coding analysis in grounded theory.

First, open coding. Raw texts were analyzed line by line to conceptualize theme-relevant statements. After two independent coding rounds and multiple comparison-screening-refinement cycles, 26 initial concepts were extracted. Statements sharing common themes were grouped into initial categories based on semantic attributes, each abstractly labeled (examples in Table 3).

Table 1. Examples of open coding

Original Utterances	Initial Concepts	Initial Categories
Dunhuang historical story animations inspire sincerity, bravery, and kindness.	Historical Story Recognition	Cultural-Historical Identity
Recording China's history and millennia of Chinese culture.	Chinese Civilization Historical Perspective Identity	
Today, one can appreciate near-real cultural relics simply by using a smartphone.	Technical Convenience	Information Technology Identity
Traditional culture can be more widely disseminated globally.	Technical Effectiveness	
Unprecedented immersion	Immersive Experience	Sense of Gain
Gained preliminary understanding of lost artifacts and "developed an urge to learn more."	Deepened Understanding	
Directly felt the value and charm of Dunhuang's culture and art.	Sense of Cultural Charm	
Instilled inexplicable joy and compassion in me.	Spiritual Nourishment	
The composition and craftsmanship of Dunhuang murals are astonishing.	Exquisite Murals	Aesthetic Perception
Restored historical architecture in high-def.	High-Fidelity Restoration	
The music and narration are flawlessly harmonized.	Harmonious Soundtrack	
Allow micron-level viewing of details.	Detail Reconstruction	
Heartbreaking to see cultural relics lost.	Pain of Cultural Relic Loss	Sense of Regret
The ancient Bili instrument now has few learners.	Sorrow over the Decline of Heritage Practitioners	
Hope all global heritage sites can create digital versions.	Technological Pride	Sense of Pride
Dunhuang civilization shines like a pearl in world history.	Cultural Pride	
I open "Yunyou Dunhuang" frequently.	High Engagement Frequency	Repetitive Engagement
Played for an hour straight—couldn't stop.	Prolonged Engagement	
Must repost to reach more people.	Link Sharing	Word-of-Mouth Advocacy
Just one visit to the Sutra Cave left me overwhelmed with emotions	Emotional Narration	
Every frame is absolutely stunning.	Aesthetic Praise	
Integrate Dunhuang into education	Cultural Heritage Transmission	Tribute to Legacy
Fund Dunhuang Grotto.	Sustain Conservation	
Gratitude to Dunhuang cultural workers for preserving this brilliance on our phones.	Tribute to Guardians	
Unforgettable Mogao Grottoes visit.	In-Person Visit	Travel Behavior
I must visit Dunhuang someday to experience its beauty firsthand.	Travel Intention	

Next, Axial coding merged similar initial categories, extracting main classifications. Team members recoded to verify the 10 categories' completeness and identify potential omissions. After validation, 10 consolidated categories emerged, distilled into three core dimensions: cognitive identification, emotional resonance, and behavioral externalization.

Table 2. Examples of associative coding

Main Categorization	Categorization
cognitive identification	Cultural-Historical Identity, Information Technology Identity
emotional resonance	Sense of Gain, Aesthetic Perception, Sense of Regret, Sense of Pride
behavioral externalization	Repetitive Engagement, Word-of-Mouth Advocacy, Tribute to Legacy, Travel Behavior

Through comparative analysis of three core categories, this study proposes the "Cultural Identity Formation Pathway Based on Museum Immersive Experiences" as the central framework. A mechanism model (Figure 2) demonstrates how users cultivate cultural identity through immersive participation, analyzing post-engagement ritual efficacy. Museums anchor shared focal points via VR/AR technologies, enabling users to construct cultural cognition. Driven by emotional energies users externalize engagement through social sharing and on-site visits, completing the ritual cycle. This establishes a progressive cycle of cognitive identification-emotional resonance-behavioral externalization, reinforcing cultural identity.

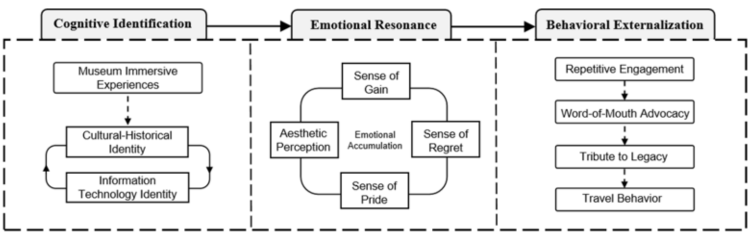

Figure 2 Cultural Identity Mechanism Model of Museum Immersive Experiences

8. Conclusion

To enhance the mutual engagement between museum immersive experiences and "GIPC", three core strategies are essential: Building emotion-driven interaction rituals rooted in participants' affective needs and cultural narratives of historical artifacts, using multisensory technologies to deepen collective value identification; Expanding ideological communication through integrated online-offline platforms where augmented reality and digital exhibitions transcend spatiotemporal constraints, amplifying cultural confidence; Implementing a "perception-identification-practice" conversion model that guides participants from immersive cultural experiences to value internalization and real-world civic action. This integrated approach demonstrates how museums can synergize technological immersion with value education, simultaneously enriching pedagogical effectiveness and cultural transmission through structured emotional-cognitive alignment.

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Research on the Dynamic Adaptability and Regional Heterogeneity of the Indicator System for Common Prosperity: Theoretical Construction and Optimization Path Exploration

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Abstract. This article analyzes the connotation of the theory of common prosperity from the perspectives of Marxist political economy, welfare economics, and development economics, and proposes three principles for constructing an indicator system, namely multidimensionality, operability, and dynamism. This study focuses on data availability, weight rationality, and dynamic adaptability, distinguishing macro and micro indicators, and proposing an innovative "three-dimensional dynamic adjustment framework" to address the issues of redistribution equity in the eastern coastal areas and the emphasis on economic growth in underdeveloped western regions, thereby implementing differentiated shared prosperity policy paths.

Key words. Common prosperity; index system

1. Introduction

As the essential requirement of Chinese path to modernization, common prosperity is not only the navigator of policy practice, but also the touchstone of academic research. Since the 18th National Congress of the Communist Party of China, "solidly promoting common prosperity" has been elevated to a national strategic level[1]. The "Opinions on Supporting the Construction of a Common Prosperity Demonstration Zone in Zhejiang" has established a provincial-level practical model for the first time, and the national "14th Five Year Plan" has listed it as a core goal for 2035 [2][3]. The accelerating trend of policy promotion and the lagging academic research have formed a clear tension: there are significant cracks in the theoretical framework, dimension selection, and regional adaptability of existing literature, which seriously restricts the precise delivery of policy tools[4][5][6][7][8][9][10]. The current research presents a triple fragmentation state: firstly, the fragmentation of theoretical construction. Marxist

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political economy emphasizes the coordination of productive forces and production relations, welfare economics focuses on equal opportunities and fair outcomes, and development economics advocates for a dynamic balance between growth and distribution. However, interdisciplinary theories have not yet formed an integrated analytical framework. Secondly, the suspension of the indicator system. Existing research either focuses on single dimensions such as the Gini coefficient, or falls into the dilemma of indicator redundancy in composite index theory, and lacks subjective perception measurement of spiritual prosperity in the digital age. Research shows that different studies exhibit significant differences in the selection of core dimensions: Ma Yiqun and Cui Lungang [11] measure the level of wealth through the dimension of "life abundance", and their tertiary indicators focus on microeconomic indicators such as per capita disposable income and per capita consumption expenditure of residents; Xu Jing's [12] dimension of "overall prosperity" includes a dual structure of "wealth income" and "public services"; The research group of the China Institute of Macroeconomics [13] emphasizes the structural indicator of the proportion of labor remuneration to GDP in the dimension of "affluence". This theoretical divergence directly leads to significant differences in research conclusions - Ma Yiqun and Cui Lungang [11]confirmed that "a prosperous life contributes the most to common prosperity," while Xu Jing[12] emphasized that "the overall prosperity index has grown rapidly, but there are significant differences in the sharing index. There is also a paradigm conflict in measuring the degree of sharing: Xu Jing [12] constructs the "Gini coefficient of income" and "urban-rural income gap" indicators through the dimension of "equilibrium level", while Xi Heng et al. [14] innovatively use the ratio method of "urban-rural common prosperity index", and Ma Mingzhao [15] turns to non economic indicators such as social security coverage. Thirdly, the dilemma of explaining regional heterogeneity. The problem of regional adaptation of indicator systems is particularly prominent in the case of Zhejiang. The Zhejiang characteristic indicator system constructed by Li Jinchang et al. [16] includes 6 process indicators and 3 outcome indicators, but it is difficult to generalize to other regions. Ma Yiqun and Cui Lungang [11] pointed out in their comparison of the process of common prosperity in Jiangsu and Zhejiang provinces that the "Sunan Model" in Jiangsu and the "Wenzhou Model" in Zhejiang have significantly different impacts on common prosperity. The Sunan model relies on the development of collective economy, while the Wenzhou model relies on the competitiveness of private economy. The differences in this development model indicate that Zhejiang's indicator system may not be able to adapt to the economic development characteristics of other regions. The analysis by Du Jin et al. [17] further reveals that the urbanization rate in East China and Northwest China has a significant promoting effect on the level of urban-rural integration development, while other regions (such as Northeast China) may not be able to replicate Zhejiang's experience due to lower urbanization levels. There is a methodological conflict between the "siphon effect" revealed by spatial econometric models [18] and the regional differences in Theil index decomposition [19], and the development stage theory urgently needs innovative dynamic adaptation models to explain the contradictions between the east and the west.

This article explores three core issues, (1) how to construct the underlying logic of a common prosperity indicator system through the construction and integration of interdisciplinary theories, (2) how to construct a classification system that integrates scientific and policy adaptability based on the principles of multidimensionality, operability, and dynamism, and (3) how to reveal the generation mechanism and governance path of regional heterogeneity through methodological innovation.

This study analyzed four dimensions: theoretical deconstruction, classification comparison, heterogeneity explanation, and policy adaptation. Innovation lies in breaking the static analysis paradigm of existing research. This article constructs a full chain research chain system of "theoretical integration, method collaboration, policy adaptation", providing scientific decision support for the practical promotion of common prosperity.

2. The theoretical basis and construction logic of the common prosperity index system

2.1. The multidisciplinary deconstruction of the theoretical connotation

2.1.1. Marxist political economy: the coordination of productive forces and production relations

Marxist political economy points out that the coordination and unity of productive forces and production relations are the core of achieving common prosperity. The development of productive forces requires the support of reasonable production relations, and common prosperity requires adjusting production relations to achieve shared results after the productive forces reach a certain level. High quality economic development is the foundation, but it needs to be accompanied by the improvement of income distribution system, narrowing of urban-rural regional gap, and equalization of public services [20]. By regulating the income of high-income groups through taxation and strengthening transfer payments for low-income groups, we can effectively promote common prosperity.[21]

2.1.2. Welfare economics: the dual dimension of equal opportunity and equal outcome

Welfare economics promotes common prosperity from the dual perspectives of equal opportunity and fair outcomes. Equal opportunities emphasize narrowing the urban-rural education gap through balanced educational resources, providing fair conditions for education, employment, and entrepreneurship in the development process [22]. Fairness in outcomes is about sharing the fruits of development and avoiding polarization [20]. By improving the social security system, enhancing risk response capabilities, narrowing the gap between urban and rural areas, regions, and groups, achieving reasonable income distribution, equal public services, and comprehensive social progress.[23]

2.1.3. Development economics: the dynamic balance theory of growth and distribution

Development economics promotes common prosperity through the dynamic balance theory of growth and distribution. This theory emphasizes that economic growth should balance fairness and sustainability in terms of speed, scale, and distribution [20]. Economic growth is the foundation, but to become rich, we must balance growth and distribution through reasonable policies. Each stage requires different strategies: in the early stages, emphasis will be placed on growth and capital accumulation, while in the later stages, emphasis will be placed on taxation and social security measures to promote fairness. The eastern coastal areas must improve distribution and public services to reduce disparities. Underdeveloped western regions require industrial support and infrastructure to promote growth.[24]

2.2. The core principle of index construction

When constructing a common prosperity indicator system, three core principles must be followed: multidimensionality, operability, and dynamism. The necessity of these three principles stems from the essential attributes and practical needs of common prosperity. The multidimensionality can comprehensively reflect their theoretical connotations, the operability ensures a scientific empirical foundation, and the dynamism adapts to the laws of development and regional differences.These principles not only ensure the scientific and comprehensive nature of the indicator system, but also enable it to adapt to the development characteristics and phased needs of different regions.

2.2.1. Multidimensional (economic, social, ecological, cultural)

The necessity of multidimensionality is reflected in the theoretical center of the concept of common prosperity. Marxist political economy emphasizes the harmonious unity of productive forces and production relations, while welfare economics emphasizes equal opportunities and fair outcomes. Development economics examines the dynamic balance between growth and distribution. A multidimensional indicator system can integrate multiple dimensions such as economy, society, ecology, and culture. The economic dimension focuses on the income level of residents, the quality of economic growth, and the optimization of industrial structure [25]; The social dimension emphasizes social equity, equalization of public services, and guarantee of people's livelihood [16]; The ecological dimension emphasizes the sustainability and livability of the ecological environment [26]; The cultural dimension emphasizes spiritual abundance, cultural inheritance, and level of civilization [20]. This multidimensionality reflects the comprehensiveness and systematicity of common prosperity, avoiding the one sidedness of single dimensional indicators (such as measuring only the income Gini coefficient).

2.2.2. Operability (data availability, weight rationality)

Ensuring scientificity and practicality, the operability of the indicator system is key: firstly, data availability, indicators must be able to be obtained from statistical yearbooks, survey materials, or official databases, and ensure their authenticity and reliability. The second is the rationality of weights, which needs to be determined by combining subjective and objective methods (such as entropy method and expert evaluation method) [27] to avoid excessive influence of indicators on the comprehensive index and accurately reflect the situation of common prosperity.

2.2.3. Dynamic nature (stage development characteristic adaptation)

The necessity of the principle of dynamism is reflected in the development laws. As the static principle ignores the differences in development stages and regional differences [28], the dynamic indicator system may be able to adapt to the characteristics of different stages. The principle of statics does not fully reflect the development trend, nor does it timely reflect the new situation and challenges of common prosperity [29]. Common prosperity is a dynamic development process, and its indicator system must be able to adapt to the development characteristics of different stages. Economic growth and material prosperity may be the main pursuits in the early stages of economic development; But the importance of social equity, ecological environment, and spiritual prosperity gradually becomes prominent after economic development reaches a certain level [28]. Therefore, the indicator system should be dynamically adjusted according to the stage characteristics of regional development. For example, indicators such as spiritual abundance and ecological environment can be given more attention in developed eastern regions, while indicators such as economic growth and infrastructure construction in central and western regions need more attention [30]. This dynamic not only reflects the phased characteristics of common prosperity, but also provides a regional basis for formulating differentiated policies.

2.3. Mainstream theoretical model controversy

In the process of constructing the indicator system for common prosperity, the selection of theoretical models has always been a focus of attention for academia and policy makers. At present, there are mainly two theoretical models that are controversial: the single dimension theory and the composite index theory, as well as the efficiency priority and fairness priority.

2.3.1. Single-dimensional theory vs. comprehensive exponential theory

The one-dimensional theory advocates measuring the level of common prosperity through a core indicator, with the most representative indicator being the income Gini coefficient. The Gini coefficient can intuitively reflect the degree of income inequality, and is easy to operate and data is readily available. However, the limitation of the one-dimensional theory is that it ignores the multidimensionality of common prosperity. Therefore, relying solely on the income Gini coefficient is difficult to fully reflect the connotation of common prosperity.

The comprehensive index theory advocates the construction of a multidimensional indicator system to measure common prosperity. The Human Development Index (HDI) covers dimensions such as per capita GDP, life expectancy, and education. Chinese scholars have proposed a similar "common wealth index" [30]. This index has the advantage of reflecting overall development at multiple levels, but faces issues such as indicator selection, weight allocation, and data availability. The overall level at the national level has improved, but there is still polarization. The regional differences in the eastern region are higher than those in the central region, and the central region is higher than the western region. The low efficiency of economic development and the low efficiency of the distribution system are considered limiting factors, and there is a "moderate trap effect" in rural areas. The Markov model indicates that the probability of level jumps is zero, and leapfrog development is a challenge.

2.3.2. Efficiency priority vs. fairness priority

There are differences between Efficiency prosperity and fairness prosperity in the path of common prosperity. In the first level indicator system, the two theoretical schools present differentiated emphasis. In terms of "wealth level", efficiency first considers the core role of economic development indicators (such as per capita GDP growth rate), focusing on improving the absolute level of income security. Fairness first requires strengthening the subjective measurement of spiritual enrichment experience in spiritual civilization indicators. Prioritizing fairness in environmental indicators and emphasize the limits of sustainable development. Efficiency first advocates for "sharing degree" and acknowledges the existence of regional differences, advocating for narrowing urban-rural disparities through market mechanisms. Fairness first advocates for the establishment of strict and binding regional differential indicators for public services, and advocates that policy intervention thresholds should be set for medical and health gap indicators. Efficiency advocates that economic growth is the foundation of common prosperity, and it is necessary to expand social wealth by improving economic efficiency. It emphasizes the driving role of market mechanisms in overall wealth growth [20] to stimulate innovation and improve efficiency. This viewpoint is consistent with the "growth first" theory in development economics, which states that in the early stages of economic development, priority should be given to economic growth and fairness should be achieved through redistribution.

Fairness priority advocates that equalization of social welfare is the core of achieving common prosperity, and insists on improving income distribution through measures such as tax regulation, social security, and government intervention. Fairness priority emphasizes the need to ensure fairness in both the starting point and the outcome in order to achieve the goal.

3. Classification system and comparative study of common wealth index

3.1. Group standard

When constructing the indicator system for common prosperity, the selection of classification criteria is essential as it directly affects the scientificity, applicability, and accuracy of the conclusions of the indicator system.

The indicators of common prosperity are divided into two levels: macro and micro. Macro level indicators such as per capita GDP and Gini coefficient [31]are applicable for provincial comparisons and guide regional coordination. At the micro level, focus on counties/communities, evaluate policy effectiveness through indicators such as satisfaction and income [32], and support local common prosperity.

The macro and micro indicators in the indicator system for common prosperity have their own advantages and disadvantages and complement each other. Macro indicators provide an overall framework, and micro indicators reflect a specific problem. When constructing an indicator system, in order to achieve comprehensive and accurate evaluation of common prosperity, it is necessary to select and combine indicators reasonably for different levels of research objects and policy objectives.

Table 1. Typical indicators of common prosperity

Level 1 indicators	Level 2 indicators	Level 3 indicators	Index interpretation
Wealth degree	economic development	Per-capita GDP growth rate	Measuring the economic growth rate of a region and reflecting the level of economic development.
	Income security	Per capita disposable income of residents	Measuring the actual disposable income level of residents and reflecting their economic strength.

	spiritual civilization	Culture, education, science and health business expenses	Measuring investment in education, culture, technology, health, and other fields to reflect the level of social civilization.
	ecological condition	land area covered with trees	Measuring the richness of forest resources in a region and reflecting the quality of the ecological environment.
	social governance	divorce rate	Measuring the degree of social harmony and reflecting family stability.
	public service	Digital infrastructure supply	Measuring the popularity of digital technology and reflecting the level of informatization.
Sharing degree	Regional gap	Extreme ratio of per capita GDP in each state and city	Measuring the gap in economic development levels between regions and reflecting coordinated regional development.
	urban-rural gap	Per capita disposable income ratio of urban and rural residents	Measuring the income gap between urban and rural areas, reflecting the coordinated development of urban and rural areas.
	income gap	Gini coefficient	To measure the fairness of income distribution, the lower the Gini coefficient, the more equitable the income distribution.
	educational inequality	Average number of students enrolled in higher education institutions per 100000 population	Measuring the fairness of resource allocation in higher education and reflecting the gap in educational opportunities.
	Regional public service gap	Coefficient of variation in the number of ordinary high schools in the region	Measuring the distribution gap of educational resources between regions and reflecting educational equity.
	Medical and health gap	Number of medical and health beds per thousand people in urban areas/Number of medical and health beds per thousand people in rural areas	Measuring the distribution gap of medical resources between urban and rural areas, reflecting medical equity.
	Ecological environment gap	Urban green coverage rate/rural green coverage rate	Measuring the gap between urban and rural ecological environments and reflecting ecological equity.
	Social security gap	Urban residents' subsistence allowance rate/rural residents' subsistence allowance rate	Measuring the gap in social security levels between urban and rural areas reflects the fairness of security.

3.2. Domestic and foreign index system comparison

In the construction and application of the indicator system for common prosperity, various representative practical schemes and academic models have been formed both domestically and internationally. This article analyzes the indicator system based on measuring the Zhejiang Common Prosperity Demonstration Zone, the indicator system based on the National Bureau of Statistics Statistical Yearbook, the international OECD Inclusive Growth Index, and the UNDP Multidimensional Poverty Index (MPI), which can better understand the characteristics, usage conditions, advantages and disadvantages of different indicator systems. The selection of these indicator systems is based on their typicality and complementarity. Domestic solutions reflect innovation in policy practice, while international solutions provide methodological references. Academic models showcase the characteristics of technical tools.

3.2.1. Domestic practice: The indicator system based on measuring the Zhejiang Common Prosperity Demonstration Zone and the indicator system based on the National Bureau of Statistics Statistical Yearbook

Zhejiang, as a model of high-quality development and common prosperity demonstration zone construction in China, has distinct local characteristics and practical directions. According to the research of Sun Hao et al. [33] and Li Jinchang et al. [16], the indicator system for common prosperity in Zhejiang mainly revolves around two main dimensions, namely "prosperity" and "sharing". The level of economic development and income is measured based on indicators such as per capita GDP, per capita disposable income of residents, and optimization of industrial structure. The Gini coefficient, urban-rural income ratio, and urban-rural consumption gap reflect indicators such as urban-rural income gap, regional income gap, and equalization of public services. The indicator system in Zhejiang Province emphasizes the dynamic updating of data, optimizing indicator weights year by year according to local needs to ensure that the indicator system can adapt to the characteristics of regional development.

The indicator system of the Statistical Yearbook of the National Bureau of Statistics focuses on national unity and macro operability, and provides standardized tools for monitoring the common prosperity of the country. Including five categories: economic development, resident income, quality of life, public services, and social equity. Reflecting economic level through per capita GDP, measuring quality of life through Engel's coefficient, and reflecting social equity through balanced education and healthcare resources. This plan highlights the universality of indicators and provides a unified standard for national monitoring. Advantages: National unity, authoritative data, and relatively easy horizontal integration. Limitations: Insufficient expression of local characteristics.

3.2.2. International Reference: OECD Inclusive Growth Index and UNDP Multidimensional Poverty Index (MPI)

The OECD Inclusive Growth Indicator System measures social inclusiveness through dimensions such as economic growth, employment, income distribution, and social welfare. It reflects economic vitality by using labor productivity, measures income inequality by Gini coefficient, and evaluates social security by the proportion of welfare expenditure. The core is to balance growth and fairness, balancing equal opportunities and fair outcomes. The advantage lies in a solid theoretical foundation and high international comparability. The limitation is insufficient coverage of poverty issues in developing countries.

The UNDP Multidimensional Poverty Index (MPI) estimates poverty from aspects such as health, education, and living standards, including indicators of child mortality and literacy rates. Overcoming a single income standard and revealing the complexity of poverty. Its advantages lie in its global applicability and multidimensional analysis; The limitation is the lack of measurement of wealth and sharing.

3.2.3. Academic Model: Entropy Empowerment System and Principal Component Analysis Composite Index (PCA)

The entropy method weighting system determines weights by calculating the entropy of indicator information, emphasizing the objectivity of data and the contribution of information. For example, in the indicator system of common prosperity, the weights of indicators such as economy, income, and public services can be objectively determined to construct comprehensive indicators, which have scientific and multidimensional evaluation advantages. Advantages: Avoiding subjective bias; Limitations: High data quality is required and susceptible to outliers.

Principal Component Analysis (PCA) composite index extracts main information through dimensionality reduction techniques, which can synthesize relevant indicators into several principal components. In the evaluation of common prosperity, synthesizing indicators such as economy, income, and quality of life into principal components to reflect the overall level of common prosperity can reduce information redundancy and improve evaluation efficiency. Advantages: Significant dimensionality reduction effect; Limitations: The explanatory power of principal component economics is weak.

4. Regional measure heterogeneity

4.1. Differences in the conclusions caused by the calculation methods

The measurement methods for the indicator system of common prosperity are diverse, and different methods may lead to significant differences in conclusions. Spatial econometric models and Theil index decomposition are two commonly used methods, each with its own characteristics in revealing regional heterogeneity.

4.1.1. Spatial measurement model

Spatial econometric models can capture spatial dependencies and heterogeneity between regions, revealing differentiation between centers and periphery. The Spatial Durbin Model (SDM) can analyze the "siphon effect" of central cities, which refers to the extraction of surrounding resources when gathering resources, leading to uneven development [18]. This to some extent explains the phenomenon of overall prosperity but widening internal disparities in the provinces where the central cities are located. This model can also use Moran's index to test the spatial autocorrelation of common prosperity and reveal regional agglomeration characteristics. Research has shown that there is a significant spatial positive correlation in China's common prosperity, such as the obvious agglomeration of neighboring regions in the east [34], indicating that policy formulation needs to consider regional spatial correlation and avoid the adverse effects of a single policy.

4.1.2. Theil index decomposition

The Theil index is an important indicator for measuring income inequality, and its decomposition can reveal the contribution of regional and intra regional differences to overall inequality. Research has shown that some regions have a higher level of common prosperity, but the contribution of intra provincial differences to overall differences is relatively small [19]. The index decomposition shows that the regional differences are more complex, mainly due to the differences between cities, towns, regions, and populations within the province [35]. Simply focusing on inter regional differences may overlook the importance of intra regional differences, thereby affecting policy accuracy and effectiveness.

4.1.3. Implications for differences in conclusions

The difference in conclusions between spatial econometric models and Theil index decomposition indicates that various methods must be widely applied to construct a common prosperity index system. The former displays regional spatial correlation and heterogeneity, while the latter deeply analyzes the contribution of regional differences. By combining the two, we can create a broader perspective for policy-making, such as reducing the siphon effect of central cities through industrial transfer, infrastructure, and other means, and strengthening regional cooperation. At the same time, we must narrow the urban-rural gap in the region and attach importance to internal coordinated development. The selection of measurement methods directly affects the scientificity of conclusions, and it is necessary to choose methods reasonably according to research objectives and policy requirements to ensure the effectiveness of conclusions.

4.2. The explanatory power of the regional development stage

The differences in regional development stages have a significant impact on the interpretation and measurement of the common prosperity system. Due to differences in economic level and industrial structure, the eastern coastal areas and the underdeveloped western regions are different. Eastern coast: prominent distribution issues. The region has a developed economy, but the problem of unequal distribution has become more severe. Indicators such as urban-rural income ratio and Gini coefficient reflect significant internal differences [25][36]. The Zhejiang demonstration zone adopts indicators such as income distribution and public equalization and reflects a high-quality development path to narrow the gap by optimizing the distribution structure. Underdeveloped western regions: Insufficient growth is the core contradiction. The absolute value of per capita disposable income is low, and the overall economic output should be prioritized for improvement. Research has shown that economic growth indicators such as per capita GDP and labor productivity have higher weights [20], while also considering ecological compensation and sustainable development indicators to avoid environmental damage.

5. Optimization path and policy enlightenment

5.1. Governance innovation under the framework of 3 D dynamic adaptation theory

The three-dimensional dynamic adaptation theory is a systematic thinking framework for solving the synergistic effects of multiple factors in complex systems. Theory can achieve organic unity of different dimensional elements by integrating dynamic feedback mechanisms. This theory specifically focuses on three main aspects: spatial adaptability (collaboration and resource sharing between regions to address regional development imbalances), temporal adaptability (adjusting indicator weights to meet the needs of different regions based on dynamic changes in development stages), and institutional adaptability (promoting efficient resource allocation and sustainable development through optimized institutional design).

The construction of a common prosperity indicator system requires the establishment of a three-dimensional dynamic adaptation model of "spatial adaptability--time adaptability--institutional adaptability". Spatial dimension alleviates the "siphon effect" and promotes the flow and sharing of resources through regional collaboration mechanisms and cross administrative element sharing platforms. By dynamically adjusting the weight of indicators in the time dimension, developed regions emphasize the balance of public services, while underdeveloped regions maintain the core position of economic growth indicators. The institutional dimension promotes sustainable innovation by improving administrative efficiency, perfecting market mechanisms, and cultivating social organizations. Theoretical logic is highly compatible with the indicator system of common prosperity, and the principle of dynamism corresponds to the adaptability of time to address differences in development stages. The principle of multidimensionality allows for multidimensional collaboration through spatial and institutional adaptability. The principle of operability is based on a dynamic feedback mechanism, providing a systematic solution to ensure scientific implementation and address regional heterogeneity.

5.2. Construction of a digital enabling policy toolbox

5.2.1. Intelligent monitoring system upgrade

Integrate government statistics, commercial data, and micro surveys to build a data platform. Satellite remote sensing night time light monitoring reflects regional economic activities; Mobile payment data shows the structural differences in consumer consumption and income; The sentiment analysis of social media dynamically evaluates the level of spiritual abundance. The toolbox effectively solves the problem of fragmented indicator systems in existing research by integrating multidimensional data platforms such as economy, society, ecology, and culture. This multidimensional data fusion improves the timeliness of indicators and effectively identifies implicit poverty and unequal opportunities to a certain extent.

5.2.2. Differentiated policy implementation path

This toolbox is based on a three-dimensional dynamic adaptation model of "spatial adaptability-temporal adaptability-institutional adaptability" and is used to design differentiated policy paths. This toolbox alleviates the "siphon effect" of central cities and promotes resource flow and shared utilization through regional collaboration mechanisms and administrative element sharing platforms. Constructing a dynamic model for charitable donations and tax incentives: Developed regions emphasize innovation in the third distribution mechanism, such as progressive inheritance tax and tax credit for equity donations; Underdeveloped regions can achieve cross regional capacity collaboration through cloud industrial parks, use block chain to build an agricultural product traceability system, implement the "digital infrastructure+industry collaboration" strategy, and solve the dilemma of "high quality and low price".

5.2.3. Elastic feedback mechanism design

Create a policy elasticity coefficient evaluation model to quantitatively analyze the moderating effect of policy intervention on regional disparities. The elastic feedback mechanism ensures the integrity and scientificity of the indicator system through real-time data feedback and dynamic optimization of policy parameters. The policy elasticity coefficient evaluation model quantifies the regulatory impact of policies on regional differences, optimizes indicator weights, and avoids single dimensional one sidedness. This mechanism includes a dual feedback loop: adjusting the proportion of vocational skills training investment based on real-time employment data, and dynamically optimizing policy parameters through intelligent algorithms in the short term; In the long run, it relies on digital twin technology that simulates policy transmission paths to predict the evolution trend of common prosperity in different scenarios, providing predictable support for strategic adjustments.

5.3. Regional heterogeneity of governance strategies

5.3.1. Eastern coastal areas

Establish a dual cycle mechanism of "innovation driven--welfare sharing" and focus on solving the problem of "high-level trap". While constructing the New Citizen Housing Security Index, promote the transformation of scientific and technological achievements through the pilot of intellectual property securitization. The supply of affordable rental housing is linked to land transfer income to ensure inclusive development in the process of urbanization. Establish a new labor relationship evaluation system that takes into account both platform development and workers' rights, and explore the distribution model of data element rights in the digital economy field.

5.3.2. Less developed western areas

Implement the collaborative strategy of "infrastructure empowerment--ecological compensation" and innovate the assessment standards for the common prosperity effect of major infrastructure projects. The accessibility equity index is introduced into transportation network planning, with a focus on improving accessibility in remote mountainous areas such as healthcare and education. Establish a linkage mechanism between carbon sequestration trading and ecological compensation, explore the value conversion path from green mountains and clear waters to golden mountains and silver mountains, and transform ecological indicators such as forest coverage into tradable regional development rights.

5.3.3. Minority concentrated region

Establish a model that links the cultivation of intangible cultural heritage inheritors with the development of characteristic tourism and establish a compensation mechanism for cultural capital. Create a positive interaction between cultural protection and industrial revitalization, restore endangered ethnic cultural symbols through digital technology, and develop immersive cultural experience products. Simultaneously establish a language resource monitoring index to dynamically evaluate the vitality of ethnic language and script usage, ensuring policy support for precise cultural inheritance.

6. Conclusion

This study systematically analyzed the dynamic adaptation mechanism of the common prosperity indicator system and the governance path of regional heterogeneity through a comprehensive and innovative interdisciplinary theoretical approach. Research has shown that in order to achieve common prosperity, it is necessary to break the boundaries of static indicator systems and effectively address the core contradictions of regional development at different stages through a framework design that combines multidimensionality, operability, and dynamism. On a theoretical level, this study provides an interdisciplinary theoretical basis for constructing an indicator system by combining the integrated analytical framework of Marxist political economy, welfare economics, and development economics. On a practical level, the "three-dimensional dynamic adaptation model" proposed in this study solves the practical dilemma of regional heterogeneity and policy tool singularity through the organic coordination of spatial, temporal, and institutional compatibility.

There are three limitations to the research, (1) the depth of theoretical integration is limited to interdisciplinary paradigms, and interdisciplinary collaboration mechanisms still need to be studied; (2) The dynamic adaptation mechanism requires high requirements for data timeliness and sensitivity to policy feedback, which may face implementation cost constraints; (3) The adaptation effect of regional heterogeneity governance strategies needs to be tested through long-term practical experience.

The theoretical value of this study lies in establishing a systematic and open analytical framework for common prosperity, and its concept of dynamic adaptation provides methodological recommendations for further research. The practical significance lies in the design of a differentiated policy toolbox in this study, which provides scientific decision support for solving the regional paradox of "growth distribution". Future research can further explore the empowerment mechanism of digital transformation on the indicator system of common prosperity, as well as the universal transformation path of China's experience from a global perspective.

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Modern Management based on Big Data VI
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Study on Resilience Measurement of China's High-Tech Manufacturing Industry Chain

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Abstract. Enhancing the resilience of the high-tech manufacturing industry chain is significant to building a manufacturing powerhouse and promoting high-quality economic development. To quantitatively study the resilience of the high-tech manufacturing industry chain, a comprehensive evaluation index system is constructed from four dimensions: resistance, recovery, reorganization, and renewal. We measured the resilience of the high-tech manufacturing industry chain across 30 provinces in China from 2008 to 2022. The results indicate that while the resilience of this industry chain has been increasing annually, the overall level remains low, and there are significant regional disparities. To strengthen the resilience of the high-tech manufacturing industry chain, it is essential to improve original innovation capacity, promote digital transformation, and achieve coordinated regional development.

Keywords. High-tech manufacturing industry; industry chain resilience; index system; measurement

1. Introduction

The report of the 20th CPC National Congress emphasizes enhancing China's economic strength and international competitiveness by strengthening industrial chain resilience and supply chain security, elevating industrial chain resilience to a strategic level for safeguarding national industrial security. As a strategically leading industry of the national economy, the high-tech manufacturing industry's resilience is crucial for building China into a manufacturing powerhouse and driving high-quality economic development. This study quantitatively assesses the resilience of provincial-level high-tech manufacturing industrial chains across China, providing a comprehensive evaluation framework to identify regional strengths and weaknesses, thereby facilitating targeted policy interventions.

Resilience theory originated in physics, characterizing an object's capacity to deform under external stress and subsequently recover its original state. The theoretical framework of resilience has evolved from equilibrium theory[1] to evolutionary theory[2], with applications expanding into management, economics, and psychology. In the current context of increasing global economic instability, industry chain resilience and

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security have become a prominent research focus, driving scholarly investigations into this domain [3]. As a conceptual integration of "industry chain" and "resilience," industry chain resilience denotes explicitly the ability of an industrial system to recover to normal operations or achieve superior performance following disruptions caused by market risks and uncertainties [4]. Current methodologies for assessing industry chain resilience primarily include the core variable approach [6], comprehensive evaluation method [8], and input-output analysis [9]. However, these methods present several limitations. The core variable approach offers only a unidimensional perspective, failing to capture the inherent complexity of industrial systems. Input-output analysis, while functional, employs overly broad industry classifications that inadequately represent emerging industries' characteristics within the value chain [10]. Consequently, many scholars adopt comprehensive indicator systems, though no universally accepted framework exists. Drawing on Martin's four-dimensional regional economic resilience framework [11], recent studies have adapted this approach to industry chain resilience, developing evaluation systems across four dimensions: resistance, recovery, reorganization, and renewal. This adaptation has proven particularly valuable in sector-specific analyses, including marine shipbuilding industry [12], copper resources industry [13], and broader industrial resilience studies [14].

In summary, existing research has yielded substantial theoretical advancements in industry chain resilience, providing valuable references for this study. However, current literature regarding resilience in high-tech manufacturing industries remains limited. Given the strategic importance of enhancing chain resilience and security, and considering the high-tech manufacturing sector's role as a national economic leader, a comprehensive assessment of its resilience development level becomes imperative.

2. Research Design

2.1. Construction of the Index System

In assessing high-tech manufacturing industry chain resilience, this study emphasizes its long-term dynamic evolution rather than merely examining impact intensity and recovery speed. Given the inherent complexity of high-tech manufacturing systems, a multidimensional approach proves essential. This research constructs a comprehensive indicator system to evaluate resilience, drawing upon Martin's economic resilience framework while adapting it to sector-specific characteristics. The selected indicators adhere to scientificity and objectivity, examining four interrelated dimensions: resistance, recovery, reorganization, and renewal.

Resistance denotes an industrial chain's capacity to maintain structural and functional stability when confronting external shocks. For high-tech manufacturing sectors, this requires both robust industrial foundations and strong institutional control to ensure operational continuity. Industrial strength, measured by enterprise quantity, total output value, and average employment, fundamentally determines stability and shock absorption capabilities. Institutional control, reflected through state-owned enterprise presence and technological dependence (the latter being a negative indicator), demonstrates national oversight of critical industries and core technologies.

Recovery characterizes an industrial chain's capacity to adapt and return to its pre-shock equilibrium following disruptions. Enhanced industrial benefits coupled with robust support systems enables faster adaptive adjustments and more effective recovery processes. Industrial benefits can be measured by labor productivity and profit rate. Industrial support, including transportation networks, communication infrastructure, and education facilities, can facilitate the flow of information in the industrial chain, reduce logistics costs, and provide talent support.

Reorganization represents the industrial chain's capacity for structural reconstruction and adaptive transformation following post-shock recovery. For high-tech manufacturing industry, enhancing reorganization capacity necessitates four key dimensions: market expansion, which provides greater developmental opportunities and resource availability; increased industrial investment, reflecting market confidence and policy support while facilitating industrial upgrading; green transition, indicative of sustainable development capabilities; and digital transformation, which improves both resource allocation efficiency and adaptability to external environmental changes.

Renewal captures the industrial chain's capacity to achieve an improved state following disruptive shocks through innovation-driven transformation. For high-tech manufacturing industry, strengthening renewal capability fundamentally depends on enhancing indigenous innovation capacity. This requires cultivating talent pools and achieving breakthroughs in core technologies, optimizing innovation infrastructure, and amplifying innovation outputs. Thus, the renewal capability can be measured by the innovation conditions, the innovation inputs, and the outputs.

The evaluation index system of high-tech manufacturing industry chain resilience is shown in **Table 1**.

Table 1. High-tech manufacturing industry chain resilience evaluation index system

Primary index	Secondary index	Tertiary index
Resistance	Industrial Foundations	Number of enterprises
		Gross output value
		Annual average number of employees
	Industrial Control	Number of state-owned Enterprises
		Technology dependence
Recovery	Industry Benefits	Labor productivity
		Profit rate
	Industrial Support	Internet broadband access ports per 10,000 people
		Length of long-distance fiber optic cable per 10,000 people per unit area
		Highway mileage per 100 square kilometers
		Railroad mileage per 100 square kilometers
		Fiscal expenditure on education
Reorganization	Market Scale	Regional GDP
		Regional GDP per capita
	Industrial Investment	Investment in the high-tech manufacturing industry
	Green Development	Energy consumption per unit of added value
	Digitalization	Expenditure on technological transformation
		Ratio of operating income of digitalized industry
Renewal	Innovation Input	R&D expenditure
		R&D personnel
	Innovation Outputs	Patent applications
		Sales revenue of new products
	Innovation Conditions	Number of enterprise-run R&D organizations

2.2. Data Source

This study employs panel data from China's high-tech manufacturing sector from 2008 to 2022 to assess industrial chain resilience across 30 provincial-level regions. Due to data availability constraints, the sample excludes Hong Kong, Macao, Taiwan, and Tibet. Primary data sources include the *China High-tech Industry Statistical Yearbook, China Statistical Yearbook*, and *China Torch Statistical Yearbook*, with missing values imputed using linear interpolation.

2.3. Research Methodology

This study combines the entropy value method and the independence weight method to determine indicator weights [13]. As objective weighting methods, the entropy value method assigns weights based on information content in indicator values, eliminating subjective bias; independence weight method utilizes inter-indicator collinearity to address information redundancy. The synthesized weights simultaneously capture both indicator variability and correlation, ensuring more accurate composite evaluation through multidimensional importance quantification.

In this paper, the entropy value method is firstly used to measure the degree of variation of the information quantity of each indicator and construct the information quantity weight. Secondly, the information overlap between the indicators is analyzed through the correlation coefficient matrix, and the independence weight is generated. Finally, the comprehensive index of China's high-technology manufacturing industry chain resilience is obtained through linear weighting calculation by combining the information quantity weight and the independence weight.

3. Results

Figure 1 presents the resilience trends of China's high-tech manufacturing industry chains at both national and regional levels (eastern, central, western regions) from 2008 to 2022. At the national level, the average level of China's high-tech manufacturing industry chain resilience demonstrated sustained growth, increasing by 97.06% from 0.136 to 0.268, though the absolute level remained relatively low with a modest annual growth rate of 4.94%. At the regional level, China's three major regions of high-tech manufacturing industry chain resilience exhibited similar growth patterns to the national average. However, the relative regional differences are significant. The eastern region has the highest resilience level, followed by the central and western regions.

The observed regional disparities may stem from several key factors. Policy effectiveness: The eastern region implements targeted, market-oriented policies that effectively promote technological innovation and industrial upgrading, whereas central and western regions demonstrate weaker policy support and precision, maintaining greater reliance on traditional industries. Industrial structure：Eastern provinces benefit from established industrial clusters with complete supply chains and significant agglomeration effects, enabling better shock absorption through inter-firm coordination. Conversely, central and western regions exhibit more fragmented industrial layouts with less mature high-tech clusters. Supporting infrastructure：The eastern region's efficient logistics networks and concentrated producer services substantially reduce operational costs and enhance adaptive capacity. Despite recent improvements, central and western regions still face logistical inefficiencies and inadequate supporting facilities. Digital transformation：Wider adoption of industrial Internet and smart manufacturing in eastern China has significantly enhanced production efficiency and supply chain flexibility, while digitalization lags in other regions, resulting in slower information flows and response capabilities. Innovation capacity: The eastern region maintains clear advantages in R&D investment intensity, talent concentration, and commercialization efficiency, generating stronger innovation-driven growth in its industrial chains.

To examine the differential contributions of various resilience dimensions in high-tech manufacturing industry chain, **Figure 2** presents the temporal trends of the four key resilience components at the national level. The index of renewal capability has always maintained a high growth rate during the observation period, with an average annual growth rate of 14.64%, which is related to the in-depth implementation of China's innovation-driven strategy and the strategy of strengthening the country with science and technology. The growth rate of recovery capability is the second highest, with an average annual growth rate of 6.12%. The perfect supporting facilities provide the high-tech manufacturing industry with good communication, logistics foundation, and talent support, reducing transaction costs. The overall level of resistance capacity is relatively stable, with a slower growth rate, probably because the high-tech manufacturing industry has been facing a situation in which its core technologies are subject to constraints, especially in recent years when the supply of technology has been cut off, the problem of "necks" has become more prominent.

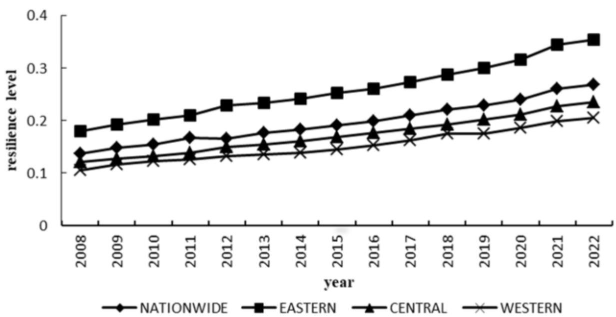

Figure 1. Resilience levels nationally and in the three regions.

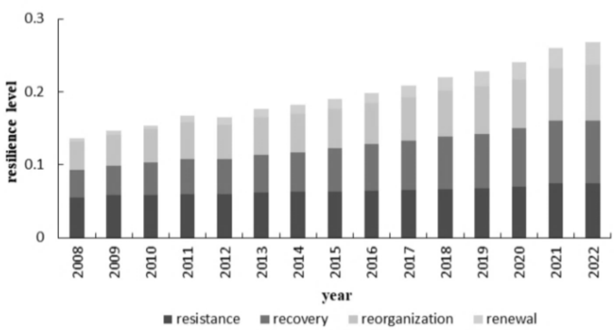

Figure 2. Four major dimensions of the resilience level.

4. Conclusion and Discussion

This paper constructs an evaluation index system from four dimensions: resistance, recovery, reorganization, and renewal. It measures the resilience level of the high-tech manufacturing industry chain in 30 provinces in China from 2008 to 2022, with the following conclusions: the average level of resilience of China's high-tech manufacturing industry chain increases year by year during the observation period, but the overall level is still relatively low, and the relative regional differences are significant. In addition, from the perspective of the four dimensions, all dimensions show an overall upward trend, among which renewal ability grows at the fastest rate, playing an important role in the process of improving the resilience level of the high-tech manufacturing industry chain.

Combined with the above research, this paper puts forward suggestions to enhance the resilience level of China's high-tech manufacturing industry chain. Firstly, the core of the high-tech industry lies in innovation and the mastery of key core technologies, and the research findings show that renewal plays an important role in the process of upgrading the resilience level of the high-tech manufacturing industry chain, so it is necessary to strengthen the basic research, improve the ability of original innovation, and fight the battle of key core technologies.

Secondly, the current digital economy is changing the production mode and operation mode of various industries, accelerating the pace of reshaping the global industrial chain supply chain pattern. The level of digitization is an important part of the recovery and reorganization of the high-tech industry. To enhance the resilience of high-tech industry chains, it is necessary to make every effort to promote the digital transformation of high-tech industry chains and promote the deep integration of new-generation information technology and high-tech industries.

Finally, it is necessary to focus on the coordinated development of the resilience of high-tech industry chains in the eastern, central and western regions. Each region can promote specialization, differentiation and characteristic development based on its resource endowment. The eastern region should continue to enhance its ability to crack the "neck" problem and form new growth poles of high-tech industry chain resilience; the central and western regions need to strengthen the role of the government's guidance and actively undertake advanced industries in the eastern region while cultivating and developing new industries, and strive to narrow the gap between the resilience level of the high-tech industry chain and that of the eastern region.

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Evaluation of Tourism Talent Structure in Central China and Its Impact on Tourism Economic Development

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Abstract. Based on the "Syrquin and Chenery Structural Change Model" principle and panel data of the tourism industry in Central China from 2011 to 2020, this study empirically analyzes the structure of tourism talents and its impact on tourism economic development. The industry structure of tourism talents in Central China deviates significantly, yet the overall deviation coefficient fluctuates downward, indicating an annual optimization trend in talent structure across various sectors. Specifically, talent shortages persist in travel agencies due to high turnover rates; the hotel industry has shown a trend towards talent surplus in recent years due to stable talent reserves; and talent gaps in tourism attractions were evident in the first three years since 2011, stabilizing thereafter. The spatial structure of tourism talents among the six provinces in Central China shows an imbalance. Shanxi Province demonstrates a relatively stable talent structure; Jiangxi Province faces relative talent shortages; Henan Province exhibits talent oversupply; and Anhui and Hunan Provinces have transitioned from talent oversupply to demand exceeding supply. ③ The spatial structure of tourism talents in Central China does not significantly impact the tourism economy, whereas the talent structures in the three industries significantly influence tourism economic development, with impacts ranked in the following order: tourism attractions > travel agencies > hotels.

Keywords. Central China; tourism talents; structure evaluation; deviation index; tourism economic development.

1. Introduction

The primary distinction between tourism enterprises and traditional production enterprises lies in the form of product output. Traditional production enterprises typically

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produce tangible physical products, while the "output" of tourism enterprises mostly manifests as intangible "service products," which essentially represent "utility." This "utility" is closely tied to human factors, as it is realized through the experience (participation) of tourists and is achieved through interpersonal interactions [1]. However, 1the "utility" produced at various stages of the tourism industry chain also differs, much like the variation in products produced by different enterprises. Travel agencies, scenic spots, and hotels are the main components of the tourism industry chain, and the "service products" they "produce" each have their own attributes. In economic terms, they belong to different economic forces, yet they share a common characteristic: they all belong to the service industry, where the most critical factor in "producing" utility is people. Thus, the country has clearly stated in the "14th Five-Year Plan for Tourism Development" that the tourism industry should implement a talent-first policy and actively build a team of cultural and tourism talents for the new era to ensure the support for cultural and tourism work.

Although Central China has demonstrated strong potential and policy support in tourism development, the imbalance in the industry structure and spatial distribution of tourism talent remains a prominent issue. This lack of coordination not only hinders tourism economic growth but also obstructs the overall optimization of the regional tourism industry. Existing studies have shown that the tourism industry's demand for talent goes beyond quantity, placing greater emphasis on quality and alignment. Talent loss, high mobility, and skill mismatches are among the primary challenges currently facing the industry [2]. Moreover, the lack of talent development and management limits the innovation capacity and market competitiveness of small and medium-sized tourism enterprises [3]. These problems are particularly evident in Central China, restricting the long-term sustainable development of the regional tourism sector.

As important components of the tourism industry chain, travel agencies, hotels, and tourist attractions must develop in a coordinated manner, as this affects the optimization of regional tourism industry structures and has a profound impact on the high-quality and coordinated development of the tourism industry. Coordinated development in economics is the "intersection" of coordination and development, referring to the equilibrium state achieved by the combined action of various economic forces to realize optimal economic development goals [4]. Considering the characteristics of the tourism industry, where people are the most critical "production" factor for "output," achieving coordinated development of the tourism industry objectively requires a coordinated development of tourism talent structures. The coordination of industry structures and spatial distribution of tourism talents directly influences and restricts the high-quality and coordinated development of the tourism industry. Therefore, exploring the relationship and patterns between the industry and spatial structures of tourism talents and tourism economic growth is not only an objective requirement for high-quality and coordinated development of the tourism economy but also holds significant theoretical and practical value for promoting healthy and stable regional economic development.

2. Literature Review

The study of talent structure is a discipline that explores the allocation of talent (human resources) and its development patterns. A review of the literature reveals that research on human capital and the impact of talent structure on economic development emerged earlier abroad. However, quantitative studies directly elucidating the interaction between the two are relatively scarce, and research focusing on the tourism economy is even rarer. Most of the existing research on talent structure examines the constraints of human capital on economic growth from the perspective of human capital. Schultz was the first to propose modern human capital theory, arguing that human capital plays a decisive role in economic growth [5]. Romer developed the endogenous economic growth model, incorporating knowledge as an endogenous variable in economic development and integrating it into the economic and technical structure of enterprises [6]. He posited that the main factors driving regional economic growth are specialized knowledge and specialized human capital. As research progressed, scholars further explored the specific pathways through which human capital impacts economic development, focusing on aspects such as educational accumulation, adjustment of talent structure ratios, and talent training. For instance, Lucas explored the impact of human capital on the economy through the process of educational accumulation, noting that the external effects of human capital can not only drive marginal efficiency increases in output but also mitigate the marginal diminishing effects of other output factors [7]; Amparo pointed out that countries with an uneven distribution of talent structure often experience lower overall economic growth rates [8]. Anther, based on the viewpoint that human resource deficits in Canada's Atlantic region pose challenges to regional economic development, discussed the crucial role of human resource development and training in regional economic growth [9]. Foreign scholars have placed greater emphasis on exploring how to cultivate and enhance talent competency in the tourism industry through quantitative or qualitative methods [10], as well as how to integrate technology and talent development into the tourism sector to improve productivity and service quality, thereby contributing to better economic outcomes [11].

Chinese scholars have made significant strides in this area of research, and numerous studies have emerged in recent years. However, the primary focus of these studies remains on the relationship between talent structure and regional economic development. For example, Wu Zhonglun et al. constructed a regional talent structure evaluation index system to reveal the relationship between talent structure and regional economic growth, positing that talent structure is a key determinant of regional economic development[12]; Liu Bing et al., using the Dalian Economic and Technological Development Zone as a case study, uncovered the general principles of talent aggregation and regional economic synergy[13]; Zhang Yanping et al., using samples from thirty provinces and cities across China, assessed and predicted the coordination between human resource structure adjustment and regional industrial structure transformation and upgrading, concluding that reasonable human resource structure adjustments will promote positive regional economic growth[14]; Wang Jianmin et al., employing statistical data from Guizhou Province from 2011 to 2017, conducted a coupling analysis, constructing two subsystems: talent structure and regional economic growth, and established a grey correlation model between the two[15]. In the field of tourism economics, Bi Xian et al., using the projection pursuit model, revealed the relationship between wellness tourism talent and the environment [16]; Liu Jia et al., through the study of the evolution of tourism talent structure, uncovered the relationship between talent structure and regional economic development [17]. Building upon this foundation, some scholars have conducted empirical studies using data from ethnic minority regions and confirmed that tourism talent resources have a positive impact on regional tourism supply-side reform and economic growth [18].

3. Research Design

3.1. Current Status of Tourism Development in Central China

Central China, comprising the provinces of Henan, Shanxi, Hunan, Hubei, Jiangxi, and Anhui, is in the economic heartland of China. It is densely populated, rich in distinctive historical and cultural heritage, and endowed with a variety of high-quality tourism resources (see Table 1), providing unique conditions for the development of tourism. With the implementation of the national "Rise of Central China" strategy, the region's economic strength has gradually increased, and the rapid development of road transportation in recent years has further promoted Central China as a significant source and destination for tourists. In 2019, before the pandemic, the six provinces in Central China recorded 3.035 billion tourist visits and total tourism revenue of 3,001.204-billion-yuan, accounting for 26.3% of the national tourism revenue, second only to the economically most developed eastern region. The international tourism revenue, calculated at constant exchange rates, reached 1,051,501 million USD, up from 809,426 million USD in 2018, marking a year-on-year increase of 29.91%[6]. In the six provinces of Central China, the proportion of tourism revenue relative to each province's GDP has remained within the 4% range.Additionally, the growth rate of tourism GDP revenue significantly exceeds.

Table 1. Summary of High-Quality Tourism Resources in the Six Central Provinces

Category / rovinces	National Important Scenic Areas	Number of 4A and Above Scenic Spots	Number of Cultural relics protection unit
Henan	Longmen Grottoes, Mount Song, Jigong Mountain, Linlü Mountain, Yuntai Mountain, Shiren Mountain, etc.	61	185
Shanxi	Mount Heng, Mount Wutai, Yungang Grottoes, Hukou Waterfall of the Yellow River, Pingyao Ancient City, etc.	23	262
Hunan	Yueyang Tower-Dongting Lake, Wulingyuan-Zhangjiajie, Shaoshan, Fenghuang Ancient City, Mount Heng, etc.	30	57
Hubei	East Lake, Three Gorges of the Yangtze River, Mount Wudang, Shennongjia, Longzhong, etc.	28	89
Jiangxi	Jinggang Mountain, Lushan Mountain, Sanqing Mountain, Wuyuan, Longhu Mountain, etc.	19	262
Anhui	Mount Huangshan, Mount Jiuhua, Mount Tianzhu, Mount Langya, Chaohu Lake, etc.	31	28

3.2. Research Methods and Data Sources

The deviation in talent structure is an important reference indicator for measuring the coordination of talent structure and optimizing the allocation of talent. In this study, the deviation in talent structure refers to the extent of deviation between the employment structure of tourism talent in travel agencies, hotels, and tourist attractions and the structure of the tourism industry, including deviations in both industry and spatial structures. Based on the universal principles of the "Syrquin and Chenery Structural

6 Source: Data Center of the Ministry of Culture and Tourism: "China Domestic Tourism Development Annual Report 2021"

Change Model" and referencing related prior research [14][15][16], the formula for calculating the deviation in tourism industry talent structure in Central China is designed as follows:

① Deviation coefficients for the talent structure in the three sectors of the tourism industry chain in Central China and the overall industry talent structure deviation coefficient:

$$Si=(Yi/Y)/(Xi/X)-1(i=1,\ 2,\ 3) \tag{1}$$

$$T=\sum |Si| \tag{2}$$

In the formula: Si represents the deviation coefficient of the talent structure in the three sectors of the tourism industry in Central China; T denotes the overall industry talent structure deviation coefficient for the tourism industry in Central China; Y stands for the industry operating revenue; Represents the number of industry employees; and i=1,2,3correspond to the three sectors: travel agencies, hotels, and tourist attractions. According to formula (1), if Si<0, it indicates an oversupply of talent in that sector; if Si=0, it indicates a balance between talent supply and demand, with no deviation; if Si>0, it signifies a talent shortage in that sector. According to formula (2), if |Si| moves further away from 0, it indicates that the deviation in the talent structure of various sectors within the tourism industry is worsening; if |Si| approaches 0, it indicates that the deviation in the talent structure of various sectors is decreasing and gradually improving.

②Deviation Coefficients for the Spatial Structure of Tourism Talent in the Six Provinces of Central China and the Overall Spatial Structure Deviation Coefficient for the Region:

$$Dj = (Ej/E)/(Pj/P)-1\ (j = 1,\ 2,\ \ldots\ldots,\ 6) \tag{3}$$

$$W= \Sigma |\ Dj\ | \tag{4}$$

In the formula: Dj represents the spatial structure deviation coefficient for tourism talent in each of the six provinces in Central China; W denotes the overall spatial structure deviation coefficient for tourism talent in the region; E represents the total tourism revenue of each province in Central China (reflecting the level of regional tourism economic development); and P represents the total number of tourism employees in each province. The variable j=1, 2…,6 corresponds to the six provinces in Central China.

- If Dj <0, it indicates an oversupply of tourism talent in that province.
- If Dj =0, it signifies a balance between tourism talent supply and demand, in line with the level of tourism economic development, with no deviation.
- If Dj >0, it indicates a shortage of tourism talent in that province.

If the spatial structure deviation coefficient moves further away from 0, it means that the spatial distribution of tourism talent is mismatched with the regional tourism economic development level. Conversely, if the coefficient approaches 0, it indicates that the coordination between the spatial structure of tourism talent and the regional tourism economic development level is gradually improving.

The data for this study is sourced from the "China Tourism Statistical Yearbook" and the "China Cultural Relics and Tourism Statistical Yearbook" for the years 2011-2020.

3.3. Measurement of Tourism Talent Structure in Central China

Based on panel data from the tourism industry in Central China for the years 2011-2020 and formulas (1) and (2), this section measures the talent structure within the three sectors of the tourism industry chain, the overall talent structure deviation, and their changes. The results are illustrated in Figure 1.

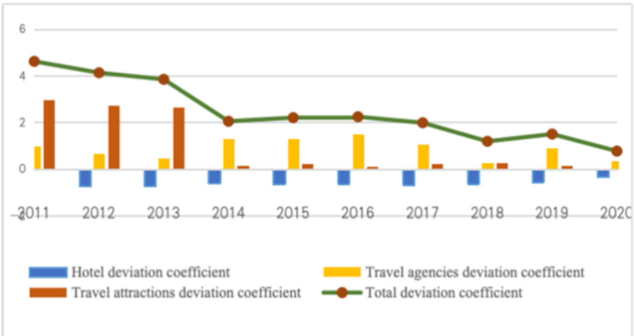

Figure 1. Deviation& Evolution of Tourism Talent Industry Structure in Central China from 2011-2020

From Figure 1, the following characteristics of the talent structure in the three sectors of the tourism industry chain in Central China and the overall talent structure can be observed:

The deviation coefficient for the talent structure in travel agencies (Si) was consistently greater than 0 over the 10 years, with an average value remaining high. The absolute value (|Si|) was relatively far from 0, indicating a significant deviation in the region's tourism talent structure. This reflects that the supply of talent in this sector was generally less than the demand. After 2013, strong macroeconomic conditions and growth in disposable income spurred rapid growth in the tourism industry, leading to a significant imbalance in the supply and demand structure of travel agency talent, except in 2018 and 2020. However, in 2020, the deviation coefficient for travel agency talent was relatively close to 0 due to the impact of the COVID-19 pandemic, which reduced travel volumes and led to the closure of some travel agencies. As a result, the trend of deviation in the talent structure of travel agencies was massively reduced due to the contraction of business.

The deviation coefficient for the talent structure in the hotel industry showed an opposite trend compared to that of travel agencies. Over the 10 years, Si was consistently less than 0, with a smaller deviation only in 2020, while the deviation was significant in other years. This indicates a substantial deviation in the region's tourism talent structure, with an oversupply of talent in the hotel industry. This phenomenon is not due to an oversupply of hotel management talent per se, but rather because the entry barriers for general positions in the hotel industry are relatively low, leading to a higher number of hotel employees. In 2020, the deviation coefficient for hotel industry talent was also reduced due to the impact of the pandemic, which caused a rapid decline in the industry's performance. Consequently, industry layoffs and employees transitioning to other fields led to a passive reduction in the deviation trend of the hotel industry's talent structure.

The deviation coefficient for the talent structure in the tourism attractions sector was consistently greater than 0 over the 10 years, although the deviation trend gradually approached balance. During the years 2011-2013, the deviation coefficient Si was at a high level, indicating that the supply of talent for tourism attractions was far from meeting demand, resulting in a shortage. This situation was related to the policy direction in 2011 when 19 provinces included leisure in their "12th Five-Year Plan" for development. After 2014, the deviation coefficient for tourism attractions gradually fluctuated closer to 0 with a smaller amplitude, demonstrating that the talent stock in tourism attractions stabilized and was relatively aligned with the development of the sector.

3.4. Measurement of the Spatial Structure of Tourism Talent in Central China

The coordination between the industry structure and spatial structure of tourism talent with the level of tourism economic development is fundamental to achieving high-quality economic development in regional tourism. While the deviation in the industry structure of tourism talent reflects the allocation of talent across different sectors, the deviation in the spatial structure of tourism talent reflects the distribution of talent across different regions. Therefore, understanding and mastering the spatial structure of talent, as well as the industry structure, is crucial for promoting high-quality development and benefits in the tourism industry.

Based on panel data from the tourism industry in Central China for the years 2011-2020 and formulas (3) and (4), this section calculates the deviation in the spatial structure of tourism talent across the six provinces in Central China and compares regional differences. The results are presented in Table 2.

Table 2. Annual Deviation in the Spatial Structure of Tourism Talent and Its Evolution in the Six Provinces of Central China

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Shanxi	-0.331	-0.324	-0.459	0.063	0.171	0.257	0.050	-0.077	-0.095	-0.331
Anhui	0.265	0.123	0.174	0.152	0.254	0.403	-0.099	-0.065	-0.128	0.122
Jiangxi	0.397	0.876	1.233	1.175	1.071	0.840	1.331	0.648	1.638	2.078
Henan	-0.453	-0.416	-0.368	-0.208	-0.344	-0.451	-0.510	-0.507	-0.515	-0.493
Hubei	0.325	0.057	-0.076	-0.066	-0.079	0.101	-0.102	0.066	0.015	-0.272
Hunan	0.004	0.014	-0.074	-0.434	-0.439	-0.409	-0.152	-0.069	-0.223	-0.393
Total W	1.774	1.809	2.384	2.099	2.358	2.461	2.244	1.432	2.614	3.690

From Table 2, the spatial structure of tourism talent and the overall talent structure in the six provinces of Central China exhibit the following characteristics:

Shanxi and Hubei: The deviation coefficients for the spatial structure of tourism talent in these provinces fluctuate slightly around 0, with ranges of ±0.21–0.38 and ±0.31–0.21, respectively. This indicates relatively stable tourism talent mobility and a talent structure that is generally aligned with the demand for tourism industry development.

Jiangxi: The deviation coefficient for tourism talent in Jiangxi has been consistently above 0 for the past decade, with a significant overall deviation. In 2020, it peaked at 2.078, with an average annual deviation of 1.13. This trend indicates a growing divergence from 0, suggesting that the tourism talent structure in this province is not well aligned with the level of tourism economic development, with demand exceeding supply. This situation arises from two main factors: (1) The province's rich red tourism and eco-tourism resources, along with active policies promoting these tourism types, have led to an imbalance between tourism talent supply and demand; (2) The COVID-19 pandemic, which began at the end of 2019, severely impacted the tourism industry, exacerbating the imbalance due to the outflow of tourism talent. Therefore, in the post-pandemic era, Jiangxi needs to focus on both increasing the supply of tourism talent and tapping into its internal potential to better align talent structure with economic development.

Anhui and Hunan: Although these provinces have experienced a transition from a shortage to an oversupply of tourism talent, the deviation coefficients remain relatively moderate, ranging from ±0.28–0.06 and ±0.02–0.37, respectively. From a macro perspective, the tourism talent structure in these provinces is generally aligned with the level of tourism economic development. This is attributed to recent reforms in tourism development models, resource integration, talent cultivation, and market system improvements in these provinces [19].

Henan: The deviation coefficient for tourism talent in Henan has been negative throughout the 10 years, indicating a consistent oversupply of tourism talent. Although the deviation is not extremely large, ranging from -0.515 to -0.208, it still suggests that the province is in a state of long-term oversupply. To ensure the healthy development of the tourism economy, it is necessary to increase investments in tourism production factors, create job opportunities, and rationalize the regional talent structure.

Overall, for the Six Province, the total deviation coefficient for the spatial structure of tourism talent fluctuates around 2.00, indicating an overall misalignment in the tourism talent structure in Central China, with a macro-level oversupply situation. The trend shows that the total deviation coefficient is moving further away from 0, indicating a growing mismatch between the tourism talent structure and the level of tourism economic development. This pattern also reflects that the tourism industry in Central China is in a period of significant growth, with strong demand for industry talent. Therefore, future development of tourism in Central China should focus on supply-side structural reforms, optimizing both the increment and adjustment of tourism talent to align the talent structure with the level of tourism economic development, aiming for high-quality growth in the tourism economy.

4. Impact of Tourism Talent Structure on Regional Tourism Economic Development in Central China

The industry and spatial structure of tourism talent are critical factors influencing the coordinated development of regional tourism industries. To further explore the impact of tourism talent structure on regional tourism economic development in Central China, a regression analysis of tourism talent structure-related variables from 2011 to 2020 in the six provinces will be conducted. This analysis aims to reveal the mechanisms through which tourism talent structure affects regional tourism economic development.

4.1. Model Construction

The total tourism revenue (TTR) from 2011 to 2020 in the central region serves as the dependent variable. The absolute values of the deviation coefficients of industry structure and spatial structure of tourism talent are used as explanatory variables. To mitigate the impact of random errors with equal variance and drastic fluctuations in variable data, natural logarithms are applied to each explanatory variable and the dependent variable: Ln|S1|, Ln|S2|, Ln|S3|, Ln|W|, Ln(TTR), The constructed model is as follows:

$$Ln(TTR)u = \alpha + \beta 1 Ln|S1|u + \beta 2 Ln|S2|u + \beta 3 Ln|S3|u + \beta 4 Ln|W|u + \varepsilon u \quad (5)$$

In the equation, S1, S2, and S3 represent the deviation coefficients of the industry structure for travel agencies, hotels, and tourist attractions, respectively. W represents the overall deviation coefficient of the spatial structure of tourism talent in the central region. A larger |W| value indicates a more imbalanced distribution of tourism talent structure, and vice versa. α is the regression constant term, $\beta 1$, $\beta 2$, $\beta 3$, and $\beta 4$ are the elasticity coefficients for the four explanatory variables, ε represents the impact of other random factors, and u represents time (years) where u = 2011, 2012, 2013, ..., 2020.

4.2. Hypothesis Testing and Result Analysis

To ensure the validity of the calculation results and avoid spurious regression due to data issues in model estimation, hypothesis testing was first conducted on each variable. Based on the principles of economics, the regression model was modified and improved. The results show that there is a significant correlation effect between the deviation of industry and spatial structures of tourism talent and regional tourism economic indicators. The goodness of fit for the regression equation is $R^2 = 0.963$, adjusted $\triangle R^2 = 0.980$, and both the accompanying P-value and the F-value from the variance analysis (F = 60.074, P-value = 0.00) meet the model conditions. Additionally, the Durbin-Watson coefficient of the regression model is 2.674, and the eigenvalues of the explanatory variables are all non-zero. The collinearity statistics VIF indices are all less than 5, indicating that there are no significant issues of autocorrelation or multicollinearity. The model has essentially passed the hypothesis testing and can proceed to regression result analysis. The regression estimation results are shown in Table 3.

Table 3. Multiple Regression Model Results

Variables	unstandardized coefficients		standardized coefficients	t	Sig.
	B	**Std. Error**	**Beta**		
constant	19.642	.065		300.173	.000
travel agencies Ln|S1|	-.175	.040	-.355	-4.398	.007
Hospitality Ln|S2|	1.684	.160	1.251	10.530	.000
Tourist attractions Ln|S3|	-.234	.017	-1.223	-13.758	.000
Space Ln|W|	-.082	.109	-.072	-.752	.486

As seen in Table 3, the elasticity coefficients of Ln|Si| (i=1,2,3) and their accompanying P-values are stable at the 5% significance level, indicating that the validation is passed. This demonstrates that the deviation in the industry structure of tourism talent significantly promotes the development of the tourism industry in the central region. However, the elasticity coefficient of Ln|W| and its accompanying P-value is unstable at the 5% significance level, indicating that the validation did not pass. Therefore, it can be concluded that the deviation in the spatial structure of tourism talent in the central region does not have a significant impact on regional tourism economic development.

Further analysis of the regression coefficients reveals that the imbalance between the supply and demand of tourism talent in travel agencies and tourist attractions (demand > supply) in the central region has resulted in a notable negative impact on regional tourism economic development. In contrast, the imbalance in the hotel industry (supply > demand) does not show the same effect. An increase of 1.00% in the deviation coefficient of the hotel industry structure promotes regional tourism economic benefits by 1.864%, indicating that the talent structure in the hotel industry is relatively stable, and the slight talent surplus does not significantly negatively impact regional tourism economic development. Instead, it even forms a certain positive influence. The results show that the deviation in the spatial structure of tourism talent in the central region has minimal impact on regional tourism economic development, whereas the deviation in the industry structure of tourism talent does have a certain impact. The order of impact effects from greatest to least is tourist attractions > travel agencies > hotels.

5. Research Conclusions and Discussion

The central region is currently in the implementation phase of the "Rise of Central China" strategy, and the rapidly developing tourism industry has become a significant engine for this strategic initiative. However, in recent years, the tourism industry has been severely impacted by the COVID-19 pandemic. As the tourism industry faces recovery in the post-pandemic era, promoting high-quality development has become a focal point of concern within the industry. Considering that, this study uses panel data from 2011 to 2020 related to the tourism industry in the central region to empirically investigate the impact of the talent industry structure and spatial structure on tourism economic development from the perspective of high-quality tourism development. The main conclusions are as follows:

The talent industry structure in the central region's tourism sector exhibits significant deviations. There is a severe shortage of specialized talent in travel agencies, resulting in a persistent supply-demand imbalance, characterized by rapid turnover and high employee resignation rates. The talent reserve in the hotel industry is relatively stable, but there has been a recent trend of increasing talent surplus and lower utilization rates. In the tourist attractions sector, there was a noticeable talent gap in the first three years starting from 2011, which has since gradually stabilized.

The spatial structure of tourism talent in the central region is unbalanced. The talent structures and stock in Shanxi and Hubei provinces exhibit stability. Jiangxi Province faces a relative shortage in tourism talent supply, while Henan Province has an excess of tourism talent. Anhui and Hunan provinces have experienced a shift from talent surplus to a situation where demand exceeds supply. Overall, there is a certain degree of irrationality in the spatial structure of tourism talent across the central region, which has consistently been in a state of supply-demand imbalance.

The spatial structure of tourism talent in the central region does not have a significant impact on regional tourism economic development. However, the talent structures in the three tourism industry sectors significantly impact regional tourism economic development. The impact strength, in order from greatest to least, is tourist attractions > travel agencies > hotels.

To optimize the tourism talent structure and promote high-quality development of the tourism economy in the central region, based on the analysis of this study, efforts should be made to improve the tourism talent industry and spatial structure through three main approaches: government, enterprises, and educational institutions.

First, government departments should play a regulatory role to promote macro-level optimization of talent structure. The government's leading role in economic development is primarily manifested through policy regulation. Therefore, the government should formulate relevant regulatory policies regarding talent cultivation, growth, and mobility based on the "medium and long-term planning for tourism economic development" to promote the optimization of tourism talent structure from a macro perspective. In terms of talent cultivation, macro-level talent cultivation goals should be set according to tourism industry development plans, with policy guidance on training programs and specialization to ensure that talent development meets industry needs. For talent growth, corresponding policy measures should be developed to provide necessary support for enterprises in hiring and utilizing talent, such as social security, housing, and professional title evaluation, to ensure relative stability and promote the optimization of the tourism talent structure. Regarding talent mobility, unreasonable policy barriers and obstacles to talent movement should be removed, and policies and mechanisms for rational talent mobility should be established to achieve balance in talent flow.

Secondly, enterprises should establish long-term talent mechanisms to stabilize talent and optimize the talent structure. Tourism enterprises are central to gathering tourism talent, and the stability of their workforce is crucial for optimizing the talent structure. Therefore, enterprises should focus on long-term strategies to ensure talent stability while optimizing the talent structure. Enterprises should seize the historical opportunities presented by the significant growth of the tourism industry by developing and adjusting their strategic plans. By continually enhancing their capabilities and growth, they can attract and retain talent. Additionally, enterprises should implement human resource management systems aligned with modern corporate practices. This includes attracting and cultivating outstanding (key) talent through targeted talent plans and improving general talent through comprehensive training programs. Such measures will enable a well-balanced and efficient talent structure based on a stable core of exceptional (key) talent.

Thirdly, educational institutions should keep pace with industry development trends to ensure that the supply of talent aligns with industry needs. As a major source of tourism talent, the quality and quantity of talent cultivated by educational institutions have a significant impact on both the talent structure and the development of the tourism industry.

Educational institutions should align their talent development programs with national and regional tourism industry development strategies to ensure that the quality and quantity of talent produced are highly coordinated with industry growth. In terms of talent cultivation, institutions should continuously update and adapt their teaching content to reflect current trends, emphasizing practical skills alongside theoretical knowledge, and focusing on the development of versatile tourism professionals [20], thus providing the tourism industry with high-quality professional talent [16].

In the context of a market economy and the autonomous movement of talent, optimizing the tourism talent structure is not an immediate process; it is akin to a "systematic project" closely linked to the level and trends of industry development. It results from the coordinated efforts of the government, enterprises, and educational institutions, embodying an integrated model of "government regulation, enterprise development, and institutional training." Through the high degree of coupling and coordination among these three entities, the goal of optimizing the talent structure is ultimately achieved.

However, the complexity of optimizing the tourism talent structure also determines the diversity of factors influencing it. Therefore, the current assessment of the tourism talent structure and its relationship with regional tourism economics revealed by this study may not fully capture the entire picture of the impact of the industry and spatial structure on the regional tourism economy. There are still theoretical gaps that need to be addressed through further in-depth research, which will help to supplement and enrich the theoretical framework of studies related to tourism talent structure.

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Promoting Cross-Border Trade: Innovative Application of AI Technology in Container Supervision

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Abstract. Cross-border trade is an important component of the global economy, and as the scale of cross-border trade continues to expand, container supervision faces many challenges. This paper first clarifies the current status of container supervision in cross-border trade and the existing problems and then discusses in depth the application of AI technology in container supervision, and also analyzes the risks and challenges faced by the application of AI technology and looks forward to the future direction of development of AI technology in container supervision. This study aims to promote the widespread application of AI technology in container supervision, improve supervision level, and facilitate global trade through a combination of qualitative and quantitative research methods, with a large number of examples.

Keywords. Cross-border trade, container supervision, artificial intelligence

1. Introduction

With the acceleration of global integration, the scale of cross-border trade is constantly growing. In order to guarantee the safety of cross-border trade, enhance logistics efficiency and speed up customs clearance, improving the level of container supervision is key. However, with the continuous growth of cross-border trade, the traditional mode of container supervision faces many challenges. Happily, the rapid development of Artificial Intelligence (AI) provides technical support for optimizing container supervision. Through the application of AI technology, intelligent supervision of containers can be realized, including intelligent identification of containers, automated security inspection, and accurate assessment of risks, which significantly improves supervision efficiency, reduces supervision costs, and enhances the accuracy and safety of supervision.

The purpose of this paper is to clarify the current status and challenges of cross-border trade container supervision, conduct in-depth research on the application, risks, and challenges of AI technology in cross-border trade container supervision, and to look forward to the future direction of development of AI technology in container supervision,

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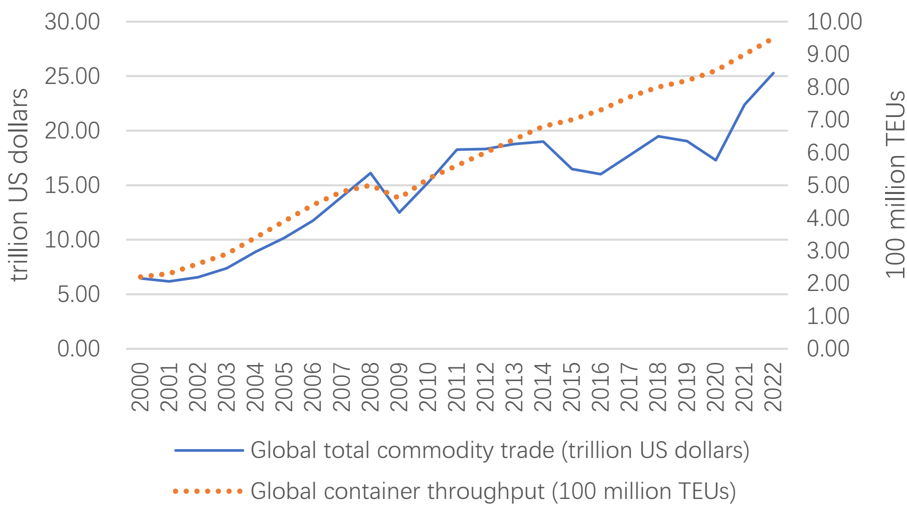
so as to provide reference for enhancing the supervision level of cross-border trade containers and promoting global trade facilitation.

2. Current status of cross-border trade container supervision

Cross-border trade is an important component of the global economy. By retrieving data on the total amount of global commodity trade and global container throughput from 2000 to 2022, the trend of cross-border trade is shown in Figure 1. The global container throughput is steadily increasing, with an average annual growth rate of about 6.9%. Due to various factors, the total amount of global commodity trade has shown an upward trend despite some setbacks, with an average annual growth rate of about 6.5%. There is a positive correlation between the total amount of global commodity trade and the global container throughput.



Data source: Official websites of the World Trade Organization (WTO) and the International Association of Ports and Harbors (IAPH)

Figure 1. Cross-border trade status from 2000 to 2022

At present, cross-border trade container supervision mainly involves cargo declaration and document audit, container inspection, container tracking and monitoring, port security management and other links. However, with the continuous expansion of the scale of cross-border trade, the traditional supervision model is difficult to meet the growing demand for supervision, container supervision work is facing many challenges.

2.1 Low supervision efficiency

The traditional way of container supervision mainly relies on manual operation, low efficiency of document audit, difficult to quickly identify false declarations, difficult to comprehensively check all containers, difficult to meet the needs of enterprises for rapid customs clearance[1][2], relying on manual risk assessment can easily lead to misjudgments or omissions. For example, at ports and customs checkpoints, staff need to manually check container numbers, check cargo lists and conduct physical inspections, which is not only time-consuming and labor-intensive, but also prone to omissions.

2.2 High supervision costs

Documentary audit, manual inspection and so on need to invest a lot of manpower and material resources, resulting in high supervision costs. According to estimates from the International Maritime Organization (IMO), the global annual cost of container supervision exceeds $10 billion, including manpower costs, equipment maintenance costs, and technology upgrade costs.

2.3 Information asymmetry

Various parties involved in international trade, such as exporters, importers, logistics companies, customs, ports, etc., may have inadequate, non-transparent, or inconsistent access to and sharing of information related to container transportation. This information asymmetry may lead to low supervision efficiency, increased trade costs, rising security risks, and increased trade disputes.

2.4 Safety hazards

Due to the lack of effective monitoring methods, containers are prone to cargo loss, damage, or illegal exchange during transportation, causing significant losses to both trading parties. Terrorism, smuggling, tax evasion and other illegal activities also pose a serious threat to the safety of container transportation, and it is necessary to strengthen container safety supervision.

In order to address these challenges, governments and international organizations are striving to find solutions. For example, the US Customs and Border Protection (CBP) has implemented the Container Security Initiative (CSI), which works with foreign ports to pre-screen high-risk containers. However, these measures still have certain limitations and cannot fully solve the problems of traditional supervision methods. Therefore, introducing AI technology has become a key measure to improve the efficiency and safety of container supervision.

3. Application of AI technology in container supervision

With the rapid development of AI technology, its application in various fields is becoming more and more extensive, and it also provides optimization ideas and technical solutions for solving the problems in traditional container supervision methods. The application of AI technology in container supervision is mainly reflected in the aspects of intelligent identification and monitoring, automated operation, data analysis and prediction, and security and compliance.

3.1 Intelligent recognition and monitoring

Through image recognition technology, AI systems can automatically recognize container number, size, and status, reduce manual operation and improve efficiency[3]; It can detect whether the container is damaged, thereby avoiding cargo loss caused by container damage; It can analyze the image of the goods in the container and determine whether the goods are consistent with the declared information. For example, Shanghai Port has achieved automatic recognition of container number and license plate by applying AI image recognition technology, which has increased the passage efficiency by more than 30%. In addition, the video surveillance system combined with AI algorithms can analyze surveillance videos in real time and detect abnormal behavior. For example, the Port of Singapore Authority (PSA) has deployed an AI-based video surveillance system in its container yard, which significantly improves the safety and supervision efficiency of the yard and reduces the workload and error rate of manual inspections.

3.2 Automated operations

The introduction of equipment such as driverless vehicles and automated cranes has greatly improved the efficiency of container loading, unloading and transportation. For example, the Port of Rotterdam in the Netherlands has implemented driverless trucks and automated crane systems, which use AI algorithms for path planning and operational control. Driverless trucks can automatically select the optimal path according to real-time traffic conditions and loading and unloading plans to transport containers from the dock to the yard; Automated cranes can automatically adjust the lifting parameters according to the weight and size of the containers, and can automatically complete container loading, unloading, and stacking. Through this system, the Port of Rotterdam has greatly improved loading and unloading efficiency, ensured operational precision and safety, and reduced labor costs. In addition, the automated operations also include intelligent scheduling systems, which optimize the resource scheduling for ports and warehouses through AI algorithms to improve the overall operational efficiency.

3.3 Data analysis and prediction

Through big data analysis and machine learning algorithms, AI system can monitor the container location and status in real time, predict the arrival time of goods by analyzing historical transportation data and real-time traffic, and optimize the transportation path, adjust the transportation plan, and optimize the resource allocation based on the prediction results; Through the analysis of historical data and market trends, it predicts the future demand for goods, and helps enterprises optimize their inventory[4]. For example, DHL, a globally famous logistics company, has developed and applied a cargo tracking system based on AI technology, which reduces the transportation cost and the risk of misdirection, and significantly improves DHL's transportation efficiency.AI technology also predicts possible risks by establishing a risk assessment model and provides an early warning for high-risk containers. For example, U.S. Customs and Border Protection (CBP) utilizes AI technology to assess the risk of imported goods, screen out high-risk goods for key supervision, and improve the efficiency and accuracy of inspection.

3.4 Safety and compliance

With the support of AI, X-ray and CT scanning technology can automatically detect prohibited or dangerous goods inside containers. Airports and ports have started using intelligent security systems to inspect containers. For example, the port of Rotterdam in the Netherlands and U.S. Customs and Border Protection (CBP) have already applied AI-assisted X-ray scanning systems that can automatically identify prohibited items such as firearms, drugs, and explosives, and issue timely alerts. In addition, AI technology can also be used for compliance management, automatic review of transportation documents, ensuring compliance with international trade regulations, and reducing the risk of violations[5].

The application of AI technology in container supervision has greatly improved the efficiency, accuracy, and safety of supervision, reduced labor costs, and provided strong support for the intelligent development of cross-border trade container supervision. The intelligence of container supervision is the core link of intelligent port construction, which directly affects the management level and throughput capacity of the port[6][7].

4. Challenges of AI technology in container supervision

Although AI technology has shown great potential in cross-border trade container supervision, its application still faces many challenges.

4.1 Data privacy and security issues are an important challenge [8]

AI systems require a large amount of data for training and optimization, including sensitive content such as container transportation information, cargo details, and customer information. How to fully utilize these data while ensuring data privacy and security is a key issue in the application of AI technology.

4.2 The risk of algorithmic bias cannot be ignored

There is a possibility of unfair, inaccurate, or discriminatory outcomes in the decision-making or prediction process of AI systems due to data, model design, or other factors. This bias may lead to unfair treatment of different types of goods or businesses, and even raise ethical, legal, and social issues.

4.3 Technology cost is an unavoidable reality

The development, deployment, and maintenance of AI systems require various resource inputs, including funds, time, manpower, and computing resources, which may be a huge burden for some small and medium-sized enterprises and ports.

4.4 Standardization issues also constrain the widespread application of AI technology

At present, the trade documents, data formats, and supervision requirements in different countries and regions are inconsistent, which increases the difficulty of information integration, leads to errors or delays in information transmission, and also limits the compatibility and applicability of AI systems in different environments.

5. Future development of AI technology in container supervision

In order to address the challenges of AI technology in container supervision, future research and development can start from the following aspects.

5.1 Strengthen data privacy and security protection

Establish a perfect data security protection mechanism to prevent risks such as data leakage and abuse. By using blockchain technology, the transparency and non-tamperability of data can be ensured, thus enhancing the security and credibility of data [9]. For example, blockchain can be used to record the transportation data of containers, ensuring the authenticity and integrity of the data, and preventing data from being tampered with or leaked.

5.2 Eliminate algorithmic bias

Eliminating algorithmic bias of the AI system needs to start from multiple aspects such as data, algorithm design, model evaluation, and governance mechanisms, combined with technical means and ethical norms, to ensure the fairness and credibility of the AI systems and avoid unfair treatment of different types of goods or enterprises.

5.3 Reduce technology costs

By developing open-source AI platforms and sharing technological resources, the development and application costs of AI systems can be reduced to make them affordable for more enterprises and ports. For example, an international cooperation platform can be established to share AI technology and resources, and jointly promote the application of AI technology in container supervision to facilitate global trade.

5.4 Build an intelligent supervision platform

Integrate data from all parties through the platform to realize information sharing and collaboration. For example, China has integrated information from customs, taxation, logistics and other departments through the "Single Window" platform, which improves data transparency and customs clearance efficiency. The EU realizes information sharing among member states through the Unified Customs Data System (UCC), which reduces information asymmetry, realizes the interconnection of customs data among member states, and improves the supervision efficiency of cross-border trade. Establish a cross-border information sharing platform (such as the WCO Data Model of the World Customs Organization) to promote data exchange among customs, ports and enterprises.

5.5 Promote the standardization process

By formulating unified international standards, the compatibility and applicability of AI systems in different environments can be improved, promoting the widespread application of technology. For example, promoting standardization of international trade documents and data (such as UN/EDIFACT standards) to reduce inconsistency in information transmission. The World Customs Organization (WCO) and the International Maritime Organization (IMO) can take the lead in developing international standards for cross-border trade customs supervision, as well as international standards for cross-border trade container supervision[10], to promote the adoption of the same technical standards and processes by countries and regions.

In recent years, due to multiple unfavorable factors such as the escalation of geopolitical conflicts and the rise of trade protectionism, the growth of global cross-border trade has slowed down. Especially in container supervision, in order to prevent AI from being used as a political tool to implement unfair competition, it is necessary to do a good job in technical prevention and control design, establish institutional guarantee mechanisms, and implement transparency measures at the execution level.

6. Conclusion

This study clarifies the current status and problems in the supervision of containers in cross-border trade and analyzes the application of AI technology in intelligent recognition, automated operation, data analysis and prediction, safety and compliance, and other aspects. The results show that AI technology can strongly enhance supervision efficiency, reduce supervision costs, and improve supervision accuracy and security. However, the application of AI technology also faces many challenges such as data privacy, technology cost, information sharing, and standardization. Future research and development should focus on addressing these challenges, promoting the widespread application of AI technology in container supervision, advancing the construction of smart ports, and promoting the prosperous development of global trade. The limitation of this study is that it only proposes the idea of innovative application of AI technology in container supervision, but does not provide specific technical solutions for the use of AI, which requires professionals to conduct more in-depth research.

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Exploration of Spatial Differentiation Characteristics and Influencing Factors of Homestays in Hunan Province

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Abstract. This study focuses on the spatial differentiation characteristics and multi-dimensional influencing mechanisms of homestays in Hunan Province. Based on data from 6,508 homestays collected from OTA platforms such as Meituan and Ctrip before March 2024, the study uses ArcGIS software combined with spatial analysis methods such as the Nearest Neighbor Index, kernel density estimation, and Lorenz curve. The findings reveal that the spatial distribution of homestays in Hunan presents an overall pattern of "dense in the east and sparse in the west, with agglomeration differentiation." Key factors influencing the spatial layout of homestays include university agglomeration, transportation accessibility, and the endowment of tourism resources. Notably, the "education-driven" agglomeration effect centered around higher education institutions is a unique spatial feature in Hunan, differentiating it from other regions where transportation or tourist attractions serve as the core drivers of spatial layout. Furthermore, this study identifies the collaborative impact of multiple factors at the regional scale and the dynamic evolution of spatial patterns, shedding light on the inherent logic of cultural-tourism spatial reconstruction. The findings provide significant empirical support and decision-making references for Hunan's efforts to promote a "university-tourist attraction-transportation" three-dimensional collaborative governance system and formulate cultural tourism integration policies.

Keywords. Homestays, Spatial Differentiation, ArcGIS, Accessibility

1. Introduction

Traditional standardized hotels are gradually unable to meet consumers' growing demand for personalized experiences. Homestays, as a new type of accommodation, have increasingly gained favor from tourists [1]. In China, especially with the implementation of the rural revitalization strategy, the number of rural homestays has rapidly increased, becoming an important driving force for local economic development. Hunan Province

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has seen significant development in its tourism industry as a major tourist destination in recent years. In 2020, Hunan received 693 million domestic and international tourists, with a total tourism income of 826.195 billion RMB, accounting for 19% of the GDP [2]. Against this backdrop, the homestay industry, particularly in rural tourism, has flourished, providing tourists with opportunities to deeply engage with local culture and becoming a key factor in driving rural economic and social development.

However, despite the rapid growth of the homestay industry, it still faces development bottlenecks, especially in terms of spatial distribution. Multiple factors, including the natural environment, tourism resources, transportation conditions, local government policies, investments, and community participation influence the distribution of homestays. The scientific planning of the spatial layout of homestays has become a critical issue for achieving high-quality development [3]. How to promote the growth of homestays while optimizing their spatial layout and improving service quality has become a key that needs to be addressed.

Although there has been considerable research on homestays, most studies focus on business models, management experiences, and tourist satisfaction, while research on the spatial distribution and influencing factors of homestays remains relatively scarce. Existing studies mostly focus on the impact of single factors (such as tourism resources, and transportation conditions) on homestay distribution, lacking systematic analysis of the combined effects of multiple factors [4]. In recent years, scholars have begun to pay attention to the spatial differentiation characteristics and driving factors of rural homestays in Hunan Province. However, existing studies have mainly summarized the industrial driving factors in relatively concentrated areas based solely on POI data [5]. Although some studies have begun to examine the spatial agglomeration patterns and driving mechanisms of homestays in typical scenic areas such as the Wuling Mountain region in Zhangjiajie [6], there remains a lack of systematic research at the provincial level in Hunan. Studies focusing on the spatial structure of homestays driven by multiple factors at the regional scale are still relatively limited.

This study takes Hunan Province as a case to focus on the spatial differentiation characteristics of homestays and their multidimensional influencing factors. It explores key dimensions such as transportation accessibility, resource endowment, and policy support, aiming to overcome the limitations of previous studies that focused primarily on typical scenic areas or localized clusters. A province-wide spatial analysis is conducted using spatial analysis tools and geographical detection methods to identify the types of spatial agglomeration and regional disparities of homestays. Furthermore, a comprehensive analytical framework of driving mechanisms is constructed to quantify the explanatory power of various factors and systematically reveal the evolutionary patterns of the rural homestay spatial structure in Hunan Province. The findings enrich the theoretical understanding of homestay agglomeration effects at the provincial scale and offer practical guidance for local governments to optimize homestay development layouts, formulate differentiated support policies, and assist homestay operators in making informed location decisions, thereby promoting high-quality spatial optimization and integrated cultural-tourism development in the region.

2. Literature Review

Spatial differentiation theory originates from the disciplines of geography and economics, and it is primarily used to explain how geographical, socio-economic, and cultural disparities lead to the uneven spatial distribution of resources and services. This theory has been widely applied in the spatial pattern analysis of traditional industries and has gradually extended to the spatial layout of service sectors such as tourism, hotels, and homestays. Some scholars emphasize economic foundations and tourism resource endowments as the main drivers of hotel agglomeration, arguing that these factors enhance market visibility, customer responsiveness, and pricing flexibility [7]. Others focus on the role of transportation convenience and infrastructure improvements in either reinforcing or weakening the agglomeration effect, pointing out that hotel geographical location and surrounding amenities significantly influence pricing strategies, particularly in urban centers and popular tourist destinations [8]. Other studies highlight regional economic development levels and cultural resource richness as long-term factors affecting spatial agglomeration, arguing that the spatial distribution of hotels is shaped by a combination of regional economic strength, abundant tourism resources, and market demand. Areas with a robust economic base and concentrated tourism resources are more likely to form hotel agglomeration zones [9]. These differences in research focus reflect the theoretical pluralism in explaining the mechanisms of spatial agglomeration.

Compared to traditional hotels, homestays-as an emerging form of accommodation-exhibit distinct characteristics in their spatial distribution. Studies have shown that homestays are often located in tourist attractions or rural areas, focusing on local cultural interaction and ecological experiences [6,10]. In studies on the spatial layout of homestays in provinces such as Guangxi, Shaanxi, and Hubei, price has been identified as the primary driving factor. Homestays located near scenic spots tend to have higher prices, whereas those farther from attractions are generally priced lower [11,12]. The spatial evolution of homestay pricing demonstrates a triadic mechanism of "consumption base-landscape resources-transportation location"[13].Existing studies predominantly focus on price as a single driving factor, while giving relatively limited consideration to the synergistic effects of multiple variables such as transportation accessibility, resource endowment, infrastructure, and policy support, thus offering an incomplete understanding of the complexity of homestay spatial structures.

In urban contexts such as Chongqing and Xi' An, transportation accessibility and infrastructure conditions are key determinants influencing the spatial distribute on of homestays. In these regions, homestays are often concentrated along urban peripheries and near tourism nodes, forming a multi-level spatial clustering pattern described as "core-corridor-zone" [14,15]. These homestays typically cluster around major roadways, entrances to high-level scenic areas, and transport hubs [16]. Spatial disparities in homestay distribution are shaped by the uneven allocation of urban-rural transportation resources and the imbalanced accessibility to tourism destinations across regions. Furthermore, spatial differentiation in homestay pricing is closely related to the level of transportation convenience, tourism appeal, and infrastructure development [14]. Studies on transportation accessibility and homestay distribution have distinguished between perceived accessibility and objective accessibility, emphasizing the significant influence of transport infrastructure quality on tourists' accommodation choices [17,18]. The "accessibility buffer" theory suggests a positive correlation between transportation infrastructure density and economic growth, further highlighting its critical role in shaping the spatial distribution of homestays.

In the Jiangsu-Zhejiang region, government policies serve as crucial driving forces. Local governments in this area have supported rural homestay development through fiscal subsidies, land-use policies, and tourism integration strategies, enhancing regional homestay agglomeration and brand development [9]. Research on Mogan Mountain in

Zhejiang indicates that government guidance, coupled with entrepreneurial initiative, has driven the spatial expansion of homestays from scenic core areas to surrounding villages, forming a “micro-scale agglomeration-macro-scale expansion” pattern [19]. The case of Chongming Island highlights the importance of tripartite collaborative governance involving the government, investment firms, and residents in optimizing the spatial layout of homestays [20].

In the context of the Wulingyuan area in Hunan Province, existing studies suggest that the spatial distribution of homestays is closely aligned with star-rating classifications, natural resource endowment, and policy support [5,6] However, current research lacks comparative analysis of the spatial differentiation of homestays at the provincial scale in Hunan and across different regional development gradients. Particularly in Hunan, the spatial distribution of homestays is shaped by the interplay of multiple factors, yet the complexity of its spatial structure and driving mechanisms at the provincial level remains underexplored. This study takes Hunan Province as the research area and adopts ArcGIS software, employing Nearest Neighbor Index and Kernel Density Estimation methods, along with Lorenz Curve analysis, to investigate the spatial balance, differentiation patterns, and multidimensional influencing mechanisms of homestays in the province. The findings aim to provide empirical evidence for studies focused on regional-scale and multi-factor interaction mechanisms of homestay distribution in Hunan.

3. Homestay Agglomeration Characteristics in Hunan Province

3.1. Study Area and Data Sources

Hunan Province is in central China, covering an area of 211,800 square kilometers with a population of 66.22 million. The province features a diverse topography, predominantly mountains and hills. It has a well-developed transportation system, with a total road length of 241,900 kilometers. Hunan has a long history and is one of the cradles of Chinese civilization, rich in intangible cultural heritage, including Xiang Opera, Huagu Opera, and Xiang embroidery, showcasing the province's unique cultural heritage and artistic charm. As of 2016, Hunan Province had 292 nationally rated tourist attractions, including 8 5A scenic areas, 92 4A scenic areas, and 156 3A scenic areas. By the end of 2019, Hunan was home to three World Heritage sites and 22 national-level scenic areas, making it an important province for national forest parks and nature reserves. Hunan has rapidly developed its education sector, with 53 higher education institutions, including renowned universities such as Hunan University and Central South University, which hold high reputations within the province.

This study utilized keyword-based searches and taking the data before March in 2024.Collected data on a total of 6,508 homestays from major OTA platforms including Meituan, Ctrip, and Fliggy, thereby constructing a dataset on the spatial distribution of the homestay industry in Hunan Province. The addresses were standardized using the Baidu Maps App, and geographic coordinates were obtained through the Baidu Coordinate Picker System for the purpose of calculating specific spatial differentiation characteristics.

3.2. Research Methodology

3.2.1. Nearest Neighbor Index

The Nearest Neighbor Index (NNI) method is primarily used to explore the spatial layout characteristics of homestays, typically covering three distribution patterns: agglomeration, balanced distribution, and dispersion. The specific formula for the calculation is as follows:

$$R=r1/rE \tag{1}$$

$$rE = 1/2\sqrt{n/A} \tag{2}$$

In the formula: A represents the area of the study region; n is the sample size; rE is the theoretical nearest neighbor distance; $r1$ is the actual spatial nearest neighbor distance; and R is the Nearest Neighbor Index.

3.2.2. Kernel Density Analysis

Kernel Density Estimation (KDE) calculates the unit density of geographical feature measurements within a specified neighborhood range. The results of kernel density estimation are used to assess the degree of spatial concentration in the homestay distribution across Hunan Province. The calculation formula is as follows:

$$f(x) = \frac{1}{nh} + \sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right) \tag{3}$$

In the formula, $f(x)$ represents the kernel density estimate of the homestay; n denotes the number of homestays; h is the bandwidth, i.e., the radius of the circular domain; K is the spatial weight function, and $x-xi$ represents the distance from the estimation point to the sample point x_i.

3.2.3. Spatial Equilibrium

To further analyze the concentration characteristics of homestay distribution in Hunan Province, this study utilizes the Geographic Concentration Index and the Lorenz Curve to conduct a detailed analysis of the spatial concentration characteristics of homestays. The Geographic Concentration Index is used to measure the degree of spatial concentration of the study object. This method is employed to quantify the spatial differentiation of homestays in Hunan Province. The calculation formula is as follows:

$$G = 100\sqrt{\sum_{i=1}^{n}\left(\frac{xi}{t}\right)} \tag{4}$$

In the formula, G represents the geographic concentration index of homestays in Hunan Province, xi refers to the number of homestays in the i city or district within Hunan Province, T denotes the total number of homestays in Hunan, and n is the number of cities or districts in Hunan Province. The value of G ranges from 0 to 100. The higher the G value, the more concentrated the homestay distribution in Hunan Province; the lower the G value, the more dispersed the homestay distribution.

3.2.4. The Lorenz curve

The Lorenz curve primarily reflects the degree of distribution equilibrium of the research object across different regions. Using the formula for calculating the concentration index in the Lorenz curve, the distribution equilibrium of the homestays across different regions was further quantified. The specific calculation formula is as follows:

$$s = \frac{\sum_{i=1}^{n} y_i - 50(n+1)}{100n - 50(n+1)} \quad (5)$$

In the formula, n represents the number of cities and districts in Hunan Province, and Yidenotes the cumulative percentage of the homestay count in each city or district, ordered from largest to smallest, for the i rank.

4. Distribution Characteristics of Homestays in Hunan Province

4.1. Uneven Distribution of Homestays: More in the East, Fewer in the West

The number and distribution density of homestays in Hunan Province reflect the tourism and economic development status of different regions. According to the statistics, there are a total of 6,508 homestays in Hunan Province, with 780 in Changsha, indicating the prosperity of the accommodation and tourism industries in the capital city and its relatively high economic development. The distribution of homestays across the 14 prefecture-level cities in Hunan Province shows significant differences. The number of homestays is the highest in Chenzhou, with 953, ranking first, followed by Changsha and Xiangxi, demonstrating strong development in these areas. Xiangtan, Chenzhou, and other cities follow in the rankings.

Using the Nearest Neighbor Index to Analyze the Spatial Agglomeration of Homestays, the Nearest Neighbor Index (R) value of homestay distribution in Hunan Province is significantly less than 1, with a significance level of 0. The R values for the 14 prefecture-level cities in Hunan Province are all less than 1, with the highest being 0.361559 in Changde, followed by cities like Loudi and Yiyang, with values around 0.3. The other cities have even higher levels of agglomeration, indicating a highly concentrated distribution of homestays across the province.

Table 1. Nearest Neighbor Index Results for Homestays in Hunan Province.

Area	Average observation distance (m)	Expected observation distance (m)	R	Distribution characteristics
Changde	1356.6402	3752.1993	0.361559	Intensive
Chenzhou	495.7467	2880.2914	0.172117	Intensive
Zhangjiajie	478.9923	2355.2674	0.203371	Intensive
Hengyang	739.5151	2816.6690	0.262550	Intensive
Huaihua	1249.2669	5880.6738	0.212436	Intensive
Xiangxi	395.5826	2577.5636	0.153472	Intensive
Loudi	1155.6333	3250.6476	0.355509	Intensive
Shaoyang	1166.4356	3845.2024	0.303348	Intensive
Xiangtan	624.6078	2101.1812	0.297265	Intensive
Yiyang	1438.3051	4344.6278	0.331054	Intensive
Yongzhou	1318.0863	4134.6112	0.318793	Intensive
Yueyang	875.1023	3304.4562	0.264825	Intensive
Changsha	594.2292	2358.5807	0.251944	Intensive
Zhuzhou	1052.5302	3206.0673	0.328293	Intensive

Note: P-value is 0.0000 and all Z-values <-19.021137

The spatial distribution of homestays is uneven, with a concentration in relatively economically developed areas, particularly in the Chang-Zhu-Tan (Changsha-Zhuzhou-Xiangtan) region. In addition to Changsha, cities like Chenzhou and Xiangxi Autonomous Prefecture also have a relatively high number of homestays, forming more concentrated areas (Figure1). In contrast, regions with relatively underdeveloped economies, such as Loudi and Yiyang, have fewer homestays, with a more dispersed distribution. Most homestays are concentrated in core areas, exhibiting a cluster distribution pattern. These dispersed homestays show a spatial layout characteristic of "more in the east, fewer in the west."

Figure 1 Distribution of the number

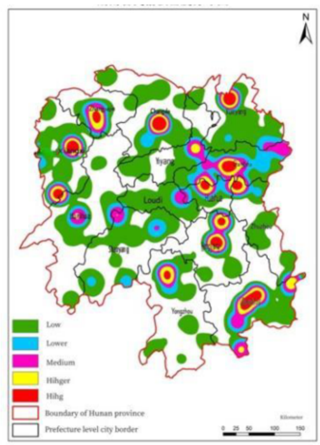

Figure 2 Distribution of nuclear density

4.2. The density of homestays in Hunan Province presents the characteristics of decentralized small aggregation

This study applies kernel density analysis to examine the spatial distribution of homestays in Hunan Province, revealing a "multi-core" pattern characterized by dense clustering in the east and sparse distribution in the west. Influenced by natural geographical factors, homestays exhibit a spatial pattern of "general aggregation with localized dispersion" (Figure 2). High-density areas include the junction of Changsha, Xiangtan, and Zhuzhou; northern Yueyang; central Changde, Zhangjiajie, Hengyang, and Chenzhou; as well as the central-southern parts of Xiangxi Autonomous Prefecture. Notably, Chenzhou's homestay clusters are located near several high-level tourist attractions. Buffer analysis further confirms that homestay hotspots often coincide with areas rich in tourism resources.

Statistical data show significant regional disparities in homestay distribution. Higher densities are concentrated in economically developed cities such as Changsha (0.0667) and Xiangtan (0.0545), demonstrating strong agglomeration effects and facilitating market formation. The Changzhutan urban agglomeration presents a notable clustering trend, supporting the growth of the homestay industry.

While Chenzhou has the largest number of homestays, its vast area leads to a lower density than Changsha and Xiangtan. Xiangxi Autonomous Prefecture, Zhangjiajie, Hengyang, and Yueyang show moderate densities, whereas regions such as Changde, Huaihua, Loudi, Shaoyang, Yiyang, Yongzhou, and Zhuzhou fall below the provincial average of 0.0300. The western regions show sparse distribution, and the province's homestay pattern is characterized by “small-scale clustering and widespread dispersion”. The findings highlight that the eastern region, especially Changzhutan, benefits from superior economic and tourism conditions, leading to more concentrated homestay development.

Table 2 Density of homestays in cities and states in Hunan Province

Area	Number	Area size（km²）	Homestay density（Per/km²）
Changde	482	18784.95	0.0257
Chenzhou	953	20407.68	0.0467
Zhangjiajie	353	9544.70	0.0370
Hengyang	496	15413.90	0.0322
Huaihua	306	27980.09	0.0109
Xiangxi	663	15777.93	0.0420
Loudi	238	8190.30	0.0291
Shaoyang	441	21137.15	0.0209
Xiangtan	272	4991.23	0.0545
Yiyang	261	11946.28	0.0218
Yongzhou	414	23291.20	0.0178
Yueyang	510	15620.49	0.0326
Changsha	780	11702.62	0.0667
Zhuzhou	339	11838.66	0.0286
Total	6508	216627.18	0.0300

4.3. The spatial distribution of homestays in Hunan Province presents overall unbalanced agglomeration features

The spatial distribution of homestays in Hunan Province exhibits a significant agglomeration effect. Overall data analysis shows that the geographic concentration index for Hunan is 29.12, which is significantly higher than the theoretical average distribution index of 26.73. Further analysis reveals that the S index for homestays in Hunan is 0.25, meaning that the distribution of homestays across the province is notably uneven, with significant regional disparities. A lower S index value indicates more balanced distribution, while the value of 0.25 clearly shows significant imbalance.

Figure 3 Laurentz curve of homestay distribution in Hunan province

By plotting the Lorenz curve, the differences in homestay numbers across the cities and prefectures are more intuitively displayed. Specifically, Chenzhou, Changsha, and Xiangxi Autonomous Prefecture have relatively concentrated homestay numbers, and these three regions account for 37% of the total homestays in the province. These areas likely benefit from better tourism resources, transportation infrastructure, and local government policy support, making them advantageous areas for homestay development. In contrast, Loudi, Yiyang, and Xiangtan have fewer homestays, each accounting for less than 5% of the total homestays in the province, indicating a lag in homestay development in these regions, possibly due to economic conditions, lack of tourism resources, or insufficient policy support.

Overall, the spatial distribution of homestays in Hunan Province presents the characteristic of "more in the east, less in the west, with small agglomeration and scattered distribution," especially in economically developed areas such as Changzhutan, where the agglomeration effect is more pronounced. This agglomerated and uneven spatial distribution reflects the profound impact of multiple factors, such as tourism resources, transportation conditions, and local government policies, on the spatial layout of homestays.

4.4. Homestay Buffer Zone Analysis in Hunan Province

4.4.1. Analysis of University Buffer Zones

Buffer zone analysis is a widely used spatial analysis method that involves creating one or more buffer zones around specific features based on a predefined distance to reveal the distribution characteristics and patterns of other elements in the surrounding areas.Hunan Province attracts many young tourists due to its rich tourism resources and unique cultural charm. Higher education institutions, as gathering places for young people, are not only densely populated but also play a positive role in driving the development of surrounding service industries. Based on this context, the study focuses on analyzing the impact of universities on the distribution of homestays.

To more accurately assess the impact of universities on homestay distribution, a buffer zone with a radius of 3 kilometers was set, which effectively covers the surrounding areas of universities while avoiding excessively wide ranges, ensuring the precision of the analysis. Using ArcGIS 10.2 software, the homestay data layer of Hunan Province was overlaid with the spatial distribution layer of higher education institutions (Figure 4). The results show that within the 3-kilometer buffer zone around universities, homestays are relatively concentrated, particularly in cities such as Huaihua, Changde, Yongzhou, and Hengyang.

Although not all homestays in each prefecture-level city are concentrated around universities, areas with higher education institutions typically feature a certain number of homestays. This indicates that the presence of universities has a positive impact on the distribution of homestays, especially in the university-adjacent areas, where a clear agglomeration effect is observed. Universities, as centers for gathering young people, not only stimulate the growth of accommodation demand but also drive the concentrated development of homestays in the surrounding areas. This highlights the important role universities play in promoting local economic development, especially in the service and accommodation sectors. This finding provides significant reference for future homestay industry layout and planning, particularly in optimizing the allocation of homestay resources around universities.

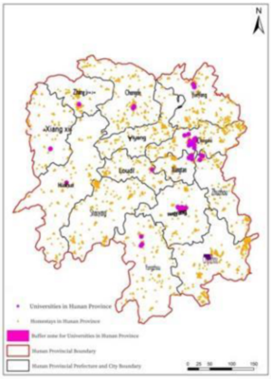

Fig. 4 Overlay of university buffer zones

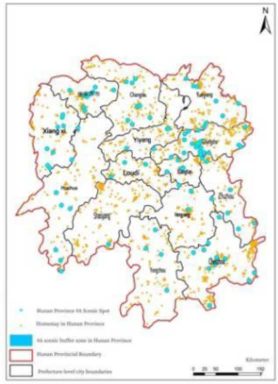

Figure 5: Tourist attraction buffer zones

4.4.2. Tourist Attraction Buffer Zone Analysis

Hunan Province, with its rich historical culture and magnificent natural landscapes, attracts many tourists, making it a nationally renowned tourist destination. To further investigate the relationship between tourist attractions and the distribution of homestays, this study selected tourist attractions above the 4A level in Hunan as the research objects and employed buffer zone analysis to reveal the spatial connection between the two.Considering that tourist attractions generally cover large areas and have a broad influence extending to surrounding regions, a buffer zone radius of 5 kilometers was set to ensure that the surrounding area of the attractions is adequately covered, allowing a more accurate reflection of the impact of tourist attractions on the distribution of homestays.

Using ArcGIS 10.2 software, this study conducted overlay analysis of the homestay sample data and the spatial data of tourist attractions in Hunan(Figure 5). The results show that homestays in cities such as Changde, Zhangjiajie, Xiangxi, Chenzhou, Zhuzhou, Hengyang, Xiangtan, and Changsha are significantly concentrated around 4A-level tourist attractions. In areas like Zhangjiajie and Hengyang, homestays show a prominent clustering trend. This indicates that tourist attractions have a significant clustering effect on the spatial distribution of homestays. The attractiveness of these attractions and the movement of tourists directly drive the concentrated development of homestays.

4.4.3. Traffic Corridor Buffer Zone Analysis

Hunan Province has a well-developed transportation network, with national roads, provincial roads, and highways forming an extensive web, which plays a crucial role in supporting regional economic and tourism development. The presence of transportation corridors not only affects travel patterns but also has a significant impact on the spatial distribution of homestays. To explore the spatial relationship between homestays and transportation corridors, this study selected major transportation routes such as national roads, provincial roads, and highways as research objects, setting the buffer zone radius to 1 kilometer to accurately reflect the direct impact of transportation routes on homestays (Figure 6).

This study conducted a spatial overlay analysis of the homestay data and transportation corridor data in Hunan. The results show that transportation corridors have a significant impact on the distribution of homestays. Most of the scattered homestays are located within the buffer zones of major transportation corridors, while clustered homestays are concentrated near intersections of transportation routes. This indicates that the density and capacity of transportation corridors directly affect the spatial layout of homestays. Homestays tend to cluster in areas with convenient transportation, especially at transport hubs, where accessibility allows tourists to easily reach these areas, promoting the concentrated development of homestays.

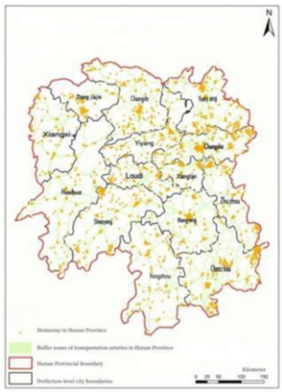

Fig 6: Transportation Artery Buffer Zones and Homestay Distribution in Hunan Province

In conclusion, transportation corridors are a key factor influencing the spatial distribution of homestays in Hunan Province. Areas with good transportation accessibility exhibit dense homestay distributions, particularly at transportation intersections, highlighting the role of transportation networks in driving the development of the homestay industry. This finding provides theoretical support for optimizing homestay layout and improving the accessibility and competitiveness of homestay services.

5. Conclusion and Management Implications

5.1. Factors Influencing Spatial Differentiation of Homestays in Hunan Province

Based on the kernel density analysis, nearest neighbor index calculation, and the spatial overlay analysis of multiple buffer zones (including universities, scenic attractions, and major transportation corridors), the spatial distribution of homestays in Hunan Province demonstrates a distinct pattern of overall imbalance and multi-factor agglomeration. On one hand, the distribution exhibits a clear “more in the east, less in the west” pattern. Regions such as Changsha, Chenzhou, and Xiangxi-with higher levels of economic development, a greater concentration of undergraduate institutions, and abundant tourism resources-have emerged as core areas for homestay clustering. Cities in the central and western regions such as Huaihua, Changde, and Shaoyang are constrained by transportation conditions, resource endowments, and policy support, resulting in fewer homestays and a more scattered spatial distribution. This finding is consistent with existing research, which suggests that areas with convenient transportation and concentrated resources are more likely to form accommodation clusters [9,10].

Furthermore, this study further validates and extends these perspectives by highlighting the multiple underlying social-structural factors influencing the spatial layout of homestays.

(1) University Clustering and Socio-Policy Factors

The impact of higher education institutions on the spatial distribution of homestays in Hunan reflects a region-specific "education-driven agglomeration" pattern. Universities not only serve as focal points for accommodation demand but also act as catalysts for the development of the local service economy. The mobility of the youth population, along with frequent activities such as examinations, academic exchanges, and campus visits, provides a stable customer base for surrounding homestays. Areas surrounding universities often benefit from relatively advanced infrastructure and supportive policy environments, which promote the upgrading of homestay formats and service quality.

(2) Transportation Accessibility and Regional Infrastructure

The degree of homestay clustering in Hunan forms a spatial logic of "transportation nodes accommodation clusters". The results of the nearest neighbor index analysis in this study further confirm the significance of transportation influence. Transportation accessibility serves as a critical geographic foundation influencing the spatial layout of homestays [8,9]. The Chang-Zhu-Tan urban agglomeration-consisting of Changsha, Xiangtan, and Zhuzhou-has the highest homestay density in the province, supported by a dense transportation network. Despite their large geographic size, western areas such as Changde and Huaihua have relatively underdeveloped infrastructure and lower tourist accessibility, leading to sparse homestay distribution and weaker clustering effects.

(3) The Agglomeration Effect of Scenic Attractions and Cultural Resources

Tourism resource clustering exerts a significant driving effect, forming a typical "attraction-driven" spatial pattern. Homestay density is significantly higher within a 5-kilometer radius of 4A-level or higher tourist attractions-such as Zhangjiajie, Fenghuang Ancient Town, and Yueyang Tower-compared to non-scenic areas, indicating a strong spatial agglomeration effect driven by attractions. In particular, the Xiangxi region, which integrates both natural landscapes and ethnic cultural resources, demonstrates that homestays serve not only as lodging facilities but also as platforms for ecological experiences and cultural exchange. This finding is consistent with existing studies on the spatial differentiation of homestays in the Wulingyuan area of Zhangjiajie Together, cultural and natural tourism resources constitute a dual mechanism of "attraction-carrying" in the spatial evolution of homestays, distinguishing their spatial layout from that of traditional lodging industries.

5.2. Management Implications

Based on the research conclusions, the following management implications are proposed:

(1) Strengthen the "University and Homestay" Synergy to Promote Education-Oriented Cultural Tourism Integration

This study identifies an emerging "education-driven" trend in accommodation consumption, with a significant spatial agglomeration of homestays around universities. Local governments are advised to promote the development of budget-friendly, culturally themed, and shared homestays tailored to youth segments in areas with dense university populations (e.g., Changsha, Hengyang, Huaihua). Integrating university student internship and entrepreneurship bases with homestay incubation platforms could foster deeper integration between youth entrepreneurship, cultural dissemination, and the accommodation industry, thereby enhancing the tourism and cultural carrying capacity within the service radius of universities.

(2) Optimize Homestay Layout at Transportation Nodes and Strengthen "Transport and Accommodation" Integrated Planning

Transportation accessibility is identified as a core variable influencing the spatial clustering of homestays. It is recommended that local governments lead the integrated spatial design of "High-Speed Rail Station-Tourist Attractions-Accommodation" corridors. In transportation hub-intensive areas (e.g., the Chang-Zhu-Tan metropolitan region, Zhangjiajie, Yueyang), coordinated development plans should support the coexistence of standardized, chain-operated, and rural-characteristic homestays around highway exits and tourism distribution centers.

(3) Establish Gradient-Based Homestay Development Zones Centered on Tourist Attractions

To promote the spatial evolution of rural homestays, functional zoning and differentiated product positioning are encouraged in villages surrounding major scenic spots. Homestay operators should be considered core drivers, with homestay associations and industry organizations serving as facilitators to foster homestay clustering around premium attractions. Destinations like Zhangjiajie and Fenghuang Ancient Town can promote the development of ethnically themed and high-end scenic homestays, peripheral buffer zones may focus on ecological experience-based and study-tourism homestays.

(4) Establish a "University-Tourist Attraction-Transportation" Triadic Spatial Collaborative Governance System

Based on this study's findings, the spatial distribution of homestays in Hunan is jointly shaped by university concentration, tourism resources, and transportation accessibility. This may include the development of a regional homestay development database, dynamic monitoring of accommodation demand in university-concentrated and key scenic areas, and the formulation of refined, tiered spatial development guidelines. Furthermore, cross-sectoral collaboration among departments of tourism, education, transportation, and housing should be promoted to construct a long-term governance mechanism for the spatial development of the homestay sector.

5.3. Limitations and Future Research Directions

Although this study systematically explores the spatial distribution characteristics and driving mechanisms of homestays in Hunan Province using spatial analysis and geographical detection methods, several limitations remain.

In terms of data sources, the study relies on static POI data, making it difficult to reveal the dynamic evolution of homestay spatial patterns. The observation that homestays around some scenic areas tend to be "numerous but uneven in quality" suggests that future research could incorporate multi-temporal data and construct time-series models to investigate the spatiotemporal evolution characteristics of homestays.

Regarding research subjects, although multiple driving factors such as transportation, resources, and policy support have been considered, the influence of micro-level mechanisms-such as host behavior and tourist perceptions has not yet been systematically examined. Future studies could integrate questionnaire surveys and in-depth interviews, incorporate the perspective of "perceived accessibility" to further explore the role of transportation perception in shaping homestay spatial distribution.

Finally, given the significant economic and social differences among provinces, the findings based on Hunan Province possess a certain degree of representativeness, but caution should be exercised when generalizing them to other regional contexts. Future research could conduct comparative studies across different provinces to enhance the generalizability and robustness of the conclusions.

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Forecasting Enterprise Operating Performance Using Environment, Social and Governance Reports

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Abstract. This study aims to forecast operating performance of enterprises using ESG reports. First, the textual analysis technique is utilized to analyze the content of ESG reports. Based on the results of content analysis, the genetic algorithm-support vector machine classifier is then used to forecast operating performance of enterprises to provide investors with a reference for decision-making of enterprise investment, thereby increasing their profitability. To achieve the above objective, the following tasks are performed: (i) a process for forecasting enterprise operating performance using ESG reports is designed, (ii) techniques involved in the process of enterprise operating performance forecasting using ESG reports are developed, and (iii) the use of the proposed approach is evaluated.

Keywords. Operating performance, ESG (Environment, Social, Governance) reports, textual analysis, genetic algorithm (GA), support vector machine (SVM)

1. Introduction

Corporate Social Responsibility (CSR) has become important indicator of corporate success, which covers three aspects, namely Environment, Social and Governance (ESG). Good ESG combined with corporate development strategies can effectively drive growth of enterprises and enhance corporate value. Therefore, in order to assist investors to learn about corporate operation status more comprehensively, how to generate forecasting information about operating performance of enterprises through analyzing ESG reports of enterprises as an important reference for whether to invest in enterprises or not have become one of the important research topics in investment decision-making.

In researches related to operating performance of enterprises and its prediction, many scholars have proposed various researches and practices in the past few years. For example, Lee et al. (2017) [1] collected financial reports and patent data from 22 pharmaceutical companies in the United States and used deep neural network algorithms such as deep belief network (DBN), support vector regression (SVR) and feedforward neural network (FNN) to establish a company's operational performance forecasting model. The model included an unsupervised learning stage and a fine-tuning stage. Song et al. (2018) [2] considered companies' industry categories and adopted 27 financial indicators to build a machine learning model for forecasting operating performance of listed companies in China. The research results indicated that the forecasting model fuzzy chance constrained least squares twin support vector machine (FCC-LSTSVM) achieved

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considerable accuracy in the prediction of enterprises' operational performance in 10 industries. Al-Dmour and Al-Dmour (2018) [3] applied the reliability of accounting information systems as the independent variable and operational performance as the dependent variable, and predicted the operating performance of enterprises with multiple linear regression (MLR) and artificial neural network (ANN). This research collected 162 pieces of original data from 202 listed companies in Jordan's financial service industry and conducted data analysis and testing through Artificial Neural Network (ANN) and mixed logistic regression (MLR). The test results showed that using the reliability of accounting information systems can significantly forecast operating performance indicators, including financial, non-financial and comprehensive indicators. Chen and Hung (2018) [4] used a meta-heuristic decision classifier (MHDC) and data collected by Taiwan's Market Observation Post System (MOPS) to forecast operating performance of enterprises. According to the experimental results, the accuracy of data testing using MHDC was higher than other machine learning models. Le et al. (2020) [5] evaluated and predicted operating performance of Vietnam logistics companies from 2014 to 2017 using necessary information (e.g., productivity, revenue, profit and operation cost) provided by managers and optimal algorithm in DEA model and gray theory model. Khan (2022) [6] discussed the literature on the correlation between ESG and operating performance of enterprises in the past 10 years and pointed out that there exists positive relationship between ESG and operating performance of enterprises, of which influence of environmental and social factors on operating performance of enterprises is more obvious. Enterprises should pay more attention to ESG to realize sustainable development. The prior studies have focused primarily on using numerical financial or non-financial data to forecast operating performance of enterprises instead of predicting operating performance of enterprises with textual non-financial data provided by ESG reports. This phenomenon often makes investors fail to have other comparatively valuable reference information to assist prediction of corporate operating performance and then investment risk of investor cannot be reduced more effectively.

This study aims to forecast operating performance of enterprises using ESG reports. First, the textual analysis technique is utilized to analyze the content of ESG reports. Based on the results of content analysis, the genetic algorithm-support vector machine classifier is then used to forecast operating performance of enterprises to provide investors with a reference for decision-making of enterprise investment, thereby increasing their profitability. To achieve the above objective, the following tasks are performed: (i) a process for forecasting enterprise operating performance using ESG reports is designed, (ii) techniques involved in the process of enterprise operating performance forecasting using ESG reports are developed, and (iii) the use of the proposed approach is evaluated.

2. Design of an Enterprise Operating Performance Forecasting Process based on ESG Reports

In this section, the process of operating performance forecasting for Taiwan listed companies is designed using ESG reports. This study employs an innovative process design, comprising the major steps of content preprocessing of ESG reports, term-pair combination, positive semantic analysis, category framework establishment for ESG reports, indicator retrieval for operating performance, positive or negative growth labeling for operating performance, establishment of feature patterns and datasets and forecasting model building, as shown in Fig. 1. Each step is described as follows.

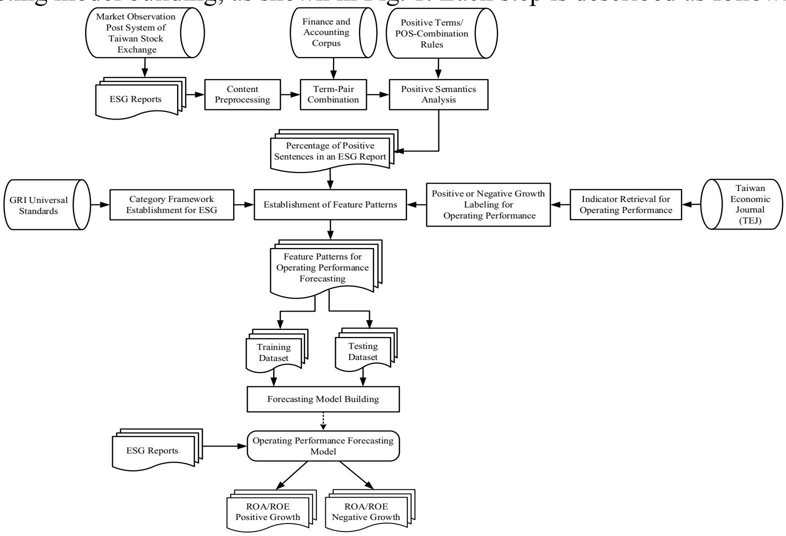

Figure 1. Enterprise operating performance forecasting process based on ESG reports.

Step 1: Content preprocessing of ESG reports: The CKIP (Chinese Knowledge Information Processing Group) Chinese parser [7][8] is utilized to conduct sentence segmentation, word segmentation and parts-of-speech (POS) tagging for the content of ESG reports retrieved by market observation post system of Taiwan stock exchange [9] to determine term sets of ESG reports.

Step 2: Term-pair combination: As the above-mentioned result of executing the sentence and word segmentation of the CKIP Chinese parser on the content of ESG reports, some words or proper nouns in the financial and accounting field may be segmented as meaningless terms, resulting in semantic errors. Therefore, it is necessary to reorganize the words that have been segmented through term-pair combination to ensure the correctness of these words.

Step 3: Positive semantic analysis: ESG reports mainly disclose relevant actions of an enterprise in three aspects, namely environment, social and governance, to make investors, suppliers and all interested parties to be clear about operation status of this enterprise and learn about its current achievements and future plan about sustainable development matters. The contents disclosed in ESG reports have positive semantics. Hence, with regard to the above sentences after POS tagging, this study adopts the POS combination-based polarity analysis method and POS combination rules proposed by Chen *et al*. (2018) [10] to conduct positive semantic analysis so as to calculate percentage of positive sentences in the content of ESG reports.

Step 4: Category framework establishment for ESG reports: This study establishes the category framework for ESG reports of Taiwan listed companies based on the ESG reports disclosed by Taiwan listed companies and referring to the GRI (Global Reporting Initiative) Universal Standard.

Step 5: Indicator retrieval for operating performance: The operating performance indicators of Taiwan listed companies are retrieved from the database of Taiwan Economic Journal, including return on assets (ROA) and return on equity (ROE) [5][6].

Step 6: Positive or negative growth labeling for operating performance: For the retrieved enterprise operating performance indicators, label positive or negative growth on a quarterly basis.

Step 7: Establishment of feature patterns and datasets: Based on the above-mentioned percentage of positive sentences in the content of ESG reports, category framework for ESG reports, and positive or negative growth labeling for operating performance indicators, the feature patterns and datasets of the enterprise operating performance forecasting model are established.

Step 8: Forecasting model building: This study uses the GA-SVM algorithm and divides the established feature pattern dataset into training dataset and testing dataset to build an enterprise operating performance forecasting model.

3. Development of Techniques for Enterprise Operating Performance Forecasting using ESG Reports

Based on the process for enterprise operating performance forecasting based on ESG reports designed in Section 2, this section introduces core steps involved in the process, including "content preprocessing of ESG reports", "term-pair combination", "positive semantic analysis", "category framework establishment for ESG reports", "indicator retrieval for operating performance", "positive or negative growth labeling for operating performance", "establishment of feature patterns and datasets", and "forecasting model building", all of which are discussed in the following subsections.

3.1. Content Preprocessing of ESG Reports

ESG reports [1] mainly use the form of textual description to disclose relevant actions of an enterprise in three aspects of environment, social and governance. Thus, the content of ESG reports released by Taiwan listed companies in 2021 and 2023 is retrieved through market observation post system of Taiwan stock exchange in this study. The CKIP Chinese Parser [7][8] is then used for sentence and word segmentation and POS tagging to obtain the meaningful terms of ESG reports.

3.2. Term-Pair Combination

In the process of preprocessing the content of ESG reports, CKIP Chinese parser may separate professional finance and accounting terms into meaningless words and cause misjudgment of semantics. To ensure correctness and completeness of these professional finance and accounting terms, this study recombines these words separated wrongly through the procedure of term-pair combination proposed by Chen and Wu (2021) [11] and the finance and accounting corpus.

3.3. Positive Semantic Analysis

ESG reports [12] mainly disclose relevant actions of enterprises in three aspects, namely environment, social, and governance in the form of textual description, semantics of which is positive. According to the results of content preprocessing and term-pair combination of ESG reports, this study adopts the POS combination-based polarity analysis method and POS combination rules proposed by Chen *et al*. (2018) [10] to analyze the positive semantics of the content of ESG reports to acquire percentage of positive sentences of the content disclosed in ESG reports.

3.4. Category Framework Establishment for ESG Reports

According to the ESG report preparation standards of GRI (Global Report Initiative), SASB (Sustainability Accounting Standards Board) and TCFD (The Task Force on Climate-related Financial Disclosures) [13], the category framework of ESG reports is established. This category framework of disclosure items for ESG reports mainly includes three aspects of environment, social and governance. Meanwhile, environmental items mainly cover water resources (E1), waste (E2), low carbon (E3), energy saving (E4), green production (E5), pollution (E6) and compliance with environmental regulations (E7), while social items contain local participation (S1), ecological education (S2) and public welfare actions (S3). Governance items involve supply chain management (G1), risk management (G2), product management (G3), customer relationship (G4) and staff (G5).

3.5. Indicator Retrieval for Operating Performance

To obtain operating performance indicators of Taiwan listed companies from the TEJ database, the TEJ Smart Wizard is used, and then its field selection procedure for retrieving operating performance indicators - ROA and ROE is executed in this order database category: IFRS finance, data name: IFRS, which is integrated into consolidated main table (cumulative) - all industries, selectable fields: ROA/ROE, data range: January 1, 2022 to December 31, 2022 and frequency: quarterly.

3.6. Positive or Negative Growth Labeling for Operating Performance

Based on the values of historical operating performance indicators ROA and ROE of Taiwan listed companies retrieved in Section 3.6, positive or negative growth in operating performance is labeled. The actual release quarter of ESG reports is used as a data unit. If the reporting quarter is i, the performance in quarter i-1 is considered the original performance, and the performance in quarter i+1 is considered the post-announcement performance. Therefore, the operating performance is calculated by subtracting the performance of quarter i-1 from that of quarter i+1.The calculated positive or negative value is used as positive or negative growth labeling for operating performance. If the calculated value of operating performance is positive, it indicates that the growth of enterprise operating performance is positive and the operating performance indicator ROA/ROE is labeled as 1. Conversely, if the negative calculated value of operating performance expresses the negative growth of enterprise operating performance and the operating performance indicator ROA/ROE is labeled as 0.

3.7. Establishment of Feature Patterns and Datasets

According to the analyzed positive semantics of the content of ESG reports in Section 3.3, the established category framework of disclosure items for ESG reports in Section

3.4 and the labeled positive or negative growth for enterprise operating performance in Section 3.6, 17 feature patterns for forecasting enterprise operating performance are established, which includes the 15 features of ESG reports, the feature of percentage of positive sentences in an ESG report (P1) and the feature of positive or negative growth of enterprise operating performance indicators ROA/ROE (R1). Meanwhile, these 15 features of ESG reports are E1: water resources, E2: waste, E3: low carbon, E4: energy saving, E5: green production, E6: pollution, E7: compliance with environmental regulations, S1: local participation, S2: ecological education, S3: public welfare actions, G1: supply chain management, G2: risk management, G3: product management, G4: customer relationship and G5: staff, as listed in Table 1.

Table 1. Feature pattern for enterprise operating performance forecasting model

Environment							**Social**		
1	2	3	4	5	6	7	8	9	10
E1	E2	E3	E4	E5	E6	E7	S1	S2	S3
Governance					**Percentage of Positive Sentences**		**ROA/ROE**		
11	12	13	14	15	16		17		
G1	G2	G3	G4	G5	P1		R1		

3.8. Forecasting Model Building

The dataset of feature pattern for forecasting enterprise operating performance conducted in Section 3.7, the dataset is divided at a ratio of 7:3 to constructed a training dataset for building a forecasting model and a testing dataset for forecasting enterprise operating performance indicators ROA and ROE. The classification model of genetic algorithm-support vector machine (GA-SVM) proposed by Wu *et al.* (2007) [14] is adopted to establish the enterprise operating performance forecasting model to improve its forecasting accuracy.

4. Experimental Results

This study retrieves the contents of the ESG reports of 782 listed companies in 2021 and 2022 from the Market Observation Post System to conduct the experiment of forecasting enterprise operating performance using ESG reports. Table 2 presents the test result by a confusion matrix. Additionally, the accuracy of the enterprise operating performance forecasting model GA-SVM and its training and testing datasets proposed in this study are compared with the classification models of Random Forest, DNN, KNN, Naive Bayes, RNN, SVM, and XGBoost. The comparison indicates that the forecasting accuracy of the adopted GA-SVM model is obviously superior to other forecasting models.

Table 2. Confusion matrix for testing the operating performance forecasting model.

Operating Performance Forecasting (ROA)		Predictive Values		Total
		Negative Growth (0)	Positive Growth (1)	
Actual Values	Negative Growth (0)	71	10	81
	Positive Growth (1)	15	159	174
Total		86	169	255
Accuracy (%)		(71+159)/255		90.20%
Operating Performance Forecasting (ROE)		Predictive Values		Total
		Negative Growth (0)	Positive Growth (1)	
Actual Values	Negative Growth (0)	68	8	76

	Positive Growth (1)	25	154	179
Total		93	162	255
Accuracy (%)		(68+154)/255		87.06%

5. Conclusions and Limitations

This paper proposed the approach for enterprise operating performance using ESG reports. The research results include the design of a process for forecasting enterprise operating performance using ESG reports, the development of enterprise operating performance forecasting techniques, and the demonstration and evaluation of the proposed enterprise operating performance forecasting approach based on ESG reports.

In establishing the feature patterns, neither industry characteristics nor any weighting schemes were taken into account, so as to differentiate industry heterogeneity.

In the future, the disclosed dimensions for the contents of ESG reports in different industries can also be analyzed to determine the effects of disclosed items on the forecasting accuracy of enterprise operating performance across different industries.

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Research on the Communication Mechanism of Strawberry Music Festival to City Image

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Abstract. Under the background of cultural and tourism integration and consumption upgrading of Generation Z, music festival has become an important carrier of urban image communication. This paper takes Strawberry Music Festival as an example, based on the actor network theory (ANT), uses the rooted theory to carry out three-level coding on the interview data of 10 senior participants, and builds a dynamic network model by combining the translation mechanism of "problematization - benefit conferring - recruitment - mobilization". The research findings are as follows: Music festival, as a cultural translation center, transforms urban cultural capital into a perceptible experience scene for young people through local symbol production such as intangible cultural heritage workshop and dialect interaction; Participants use UGC content creation and ritualized behavior to reconstruct urban cognition and drive the spread of social media; Through the optimization of infrastructure, the city interacts with the music festival to realize the dynamic update of the city image. At the theoretical level, the synergistic logic of human and non-human actors is revealed, and the application boundary of ANT in cultural events is expanded. In practice, strategies such as strengthening the accuracy of local symbol translation and optimizing the service response network are proposed to activate the long-term communication mechanism of urban image.

Keywords. Strawberry Music Festival; City image; Network modeling; Urban communication strategy; Qualitative coding.

1. Introduction

Music festival is "a group festival activity that integrates social and novel experiences with music as the carrier" [1]. Under the double background of the continuous promotion of China's cultural and tourism integration policy and the rise of consumption in the era Z, music festivals, with their characteristics of "scene experience + community communication", create a unique city image in audio-visual interaction [2]. According to the statistics of China Performance Industry Association, in the first half of 2024, 148 music festivals were held nationwide, attracting 4.634 million audiences, of which May reached the peak in the first half of the year, and the box office revenue accounted for 40.8%[3]. Existing studies mainly explore the role of music festivals in the dissemination

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of urban images from two aspects: First, by transforming the physical space of the city, such as promoting the upgrading of infrastructure and the reshaping of public Spaces, enhance urban cultural symbols and local identity [4-6]; Second, by enhancing tourists' emotional experiences, promoting their loyalty and word-of-mouth promotion, it indirectly boosts the improvement of the city's image [7-9]. However, most of these studies adopt a linear analytical perspective, ignoring the important role of non-human actors in the construction of urban space and cultural values, and failing to fully consider how the interaction among multiple actors affects the formation of the urban image. This one-sided perspective limits our understanding of the dynamic formation process of a city's image.

This study focuses on the Strawberry Music Festival, applying grounded theory and actor-network theory to systematically reveal how multiple actors (including non-human factors) collaboratively influence the dissemination path of urban images. Through this research, not only is the theoretical framework for urban image shaping enriched, but also strategic suggestions are provided for urban planners and music festival organizers to promote the transformation of urban images from short-term traffic to long-term cultural identity, achieving the value coexistence of cultural festivals and urban brands.

2. Literature review

2.1 City image and Music Festival

Urban image is the subjective perception of the public towards a city, an interaction product of objective material forms and subjective psychological evaluations. In the "urban image" theory, urban image includes five categories such as roads, boundaries, and nodes, laying the cognitive foundation of objective forms [10]; some scholars emphasize the superimposed effects of economy, culture, and media, highlighting the complexity of subjective perception [11]. Mei Baohua's three-level framework of "material facilities - administrative level - humanistic features" [12] and Cao Sui's dichotomy of "internal cultural accumulation - external behavioral expression" [13] jointly reveal the complexity of urban image construction. Currently, the academic community recognizes the diversity and complexity of urban image construction: it encompasses both the objective dimension centered on spatial cognition and the subjective dimension including cultural psychology and social practice, reflecting the urban image generation mechanism under the interweaving of a "thing-human-media" multi-system. As an activity relying on the city, music festivals not only highlight the city's cultural characteristics but also feed back to the city's brand building and dissemination through diverse experiences. In the research on the relationship between urban image and music festivals, a large number of empirical studies have shown that music festival images can significantly enhance the cultural atmosphere [4], humanistic features [5], and hardware facilities [6] of the destination at the direct impact level. At the same time, indirect indicators such as loyalty [7], tourist involvement [8], and revisit intention [9] also confirm their positive effects.

Most of the existing studies have focused on a single dimension and adopted empirical methods such as linear regression, but have not fully combined qualitative methods for systematic exploration. In this regard, it is necessary to embed qualitative paths on the basis of quantitative analysis to reveal the generation logic of the urban image in the dynamic communication system more completely.

2.2 The theory of actor network

Actor-Network Theory (ANT) provides a dynamic ontological framework for the construction of urban communication paths, revealing the networked logic of urban meaning production by emphasizing the symmetrical interaction between human and non-human actors. From the perspective of Actor-Network Theory (ANT), urban communication is not a unidirectional process of symbolic representation, but rather a heterogeneous network formed through the continuous translation mechanism by multiple actors [14]. Previous studies have attempted to apply ANT to urban communication and image construction, revealing how multiple actors collaboratively shape urban space and meaning through material spaces and discourse practices. For instance, the physical environment promotes or restricts interpersonal interaction, demonstrating non-human agency [15]; visualization tools act as "mediating actors" to regulate the interplay between community policies and the public [16]; the role of street billboards as "translation nodes" [17]. In the field of tourism culture, van der Duim et al. introduced the ANT framework, emphasizing the co-construction of practice networks by human and non-human actors, broadening the understanding of the dynamics of destination communication [18]. Domestic research also highlights that urban space communication relies on policy discourse and citizen behavior to achieve meaning translation [19]. Macfarlane and Yang proposed "the city as assemblage", emphasizing the dynamic connection between infrastructure, technological media, and human behavior, reflecting the "translation-connection" mechanism of ANT [20]. In summary, the formation of urban image is a network effect resulting from the continuous interaction of multiple actors, embodying the theoretical presuppositions of ANT regarding the symmetry of agency and network synergy. Although existing studies have quantitatively revealed the impact of music festivals on urban image and the explanatory potential of ANT for urban space, they lack an empirical network modeling approach to explain how music festivals reproduce urban image through the translation mechanism of multiple actors. This paper, combining grounded theory with interviews and coding of Strawberry Music Festival fans, explores the heterogeneous actor network and its dynamic construction mechanism, supplements the deficiency of quantitative research, and reveals the intertwined paths of urban image communication through cultural practices, spatial production, and technological devices.

3. Research Approach

This study uses the rooted theory method and in-depth interview to explore the mechanism of strawberry Music festival to promote the spread of urban image. In terms of the selection of interview samples, the purpose sampling method was mainly adopted. Recruitment information was posted on various media platforms such as Xiaohongshu and Weibo, and the audience was recruited for a fee to conduct semi-structured in-depth interviews, each lasting about 30 minutes. After obtaining the permission of the interviewees, the audio was recorded and converted into text after the interviews ended. The interviews were conducted flexibly around the research topic, and coding analysis was carried out continuously during the interviews until no new categories or concepts emerged, reaching theoretical saturation, and finally 10 audience members were interviewed. (Table 1)

Table 1 Information of Respondents

Number	Age	Region	Participation frequency
1	28	Beijing	5
2	24	Yichang	4
3	31	Shangrao	6
4	22	Jinhua	3
5	29	Heze	5
6	26	Jinzhong	4
7	19	Qingdao	3
8	34	Shangqiu	5
9	22	Guangzhou	4
10	23	Yinchuan	3

Compile the interview materials sentence by sentence in the absence of personal biases and existing thinking to uncover the initial concepts. In this study, Nvivo12 was used to initially organize the interview texts to extract meaning units and establish free nodes; Then, the key statements were continuously compared to divide the theoretical categories and sort out their concepts and attributes; Finally, elements of similar nature and content were combined to form categories, resulting in 45 concepts and 18 categories. Open coding examples are shown in Table 2.

Table 2 Examples of open coding

Open coding	**Conceptualization**	**Original statement**
A1 Word of Mouth Impact	a1 Social media users' spontaneous recommendations 8/10	I saw several people in my circle of friends Posting live videos of the Strawberry Music Festival. I was so tempted that I immediately searched for ticket information.
	a2 Previous participants Experience sharing 6/10	Brush the experience of a blogger in the small red book, the above collection card aroused my interest! He drew the PRO bracelet and went straight into the front row to see Miriam Yeung. And he gave out the secret. I really want to experience it myself!
A4 Handmade cultural symbols	a10 Intangible Cultural Heritage Workshop Pop-up store setup 2/10	There is a fashionable and cool characteristic exhibition area in Guiyang Farm, which is both retro and modern. Traditional Miao embroidery patterns and other intangible cultural heritage are created into various fashionable products, and there are a lot of people to buy.
	a11 Traditional Folk art paper-cutting Workshop set up 3/10	Guangzhou Square invited two famous paper-cutting artists to teach you paper-cutting on site. What impressed me most was a piece of work called "Old Guangzhou", which featured various kinds of Guangzhou food.
A10 Exquisite service	a25 Health care services are thoughtful 9/10	The weather is too hot, my head is a little dizzy. I saw a medical service point near the venue and came here.
	a26 Free bus to pick up music fans for night market tour 2/10	Before I only know strawberry bus is to buy tickets in advance, but when I watched the music festival to see hungry, found that Urumqi has a free bus can go to the night market.

After combing and comparing the open coding repeatedly according to cause and effect and juxtaposition, the main category is extracted. After spindle coding, 7 main categories are excavated from 18 initial categories, which are image pre-perception, cultural symbol production, cultural interaction practice, service guarantee response, cognitive construction correction and transmission and diffusion triggering. The coding process is shown in Table 3.

Table 3. Examples of spindle coding

Spindle coding	Open coding	Total mentions (proportion)
AA1 Image perception	A1 word-of-mouth impact, A2 facility evaluation, A3 star drainage	24 times
AA2 Cultural symbol production	A4 handmade cultural symbols, A5 food cultural symbols, A6 dialect cultural embedment	18 times
AA3 Cultural interaction practice	A7 Regional identity recognition, A8 group behavior patterns, A9 Ritualized bonding	20 times
AA4 Service Assurance Response	A10 service refinement, A11 emergency management, A12 compensation mechanism	22 times
AA5 Cognitive Construction revision	A13 Labeled perception, A14 Urban Trait Mapping, A15 Development mapping	15 times
AA6 Propagation and diffusion trigger	A16 triggers self-propagation, A17 media-directed, A18KOL driven	19 times

Selective coding aims to identify and extract "core categories" from major categories and systematically analyze their relationships with other categories in order to build a theoretical framework. According to the open coding and the main axis "story line" mentioned above, it can be summarized as follows: Participants' inherent impression of the city before participating in the music festival translate the music festival entity and the city entity during the participation process, so as to change the pre-impression and transmit the self-perceived positive or negative city image after the music festival. Based on this "story line", the mechanism model of Strawberry Music Festival to spread the city image is shown in Figure 1:

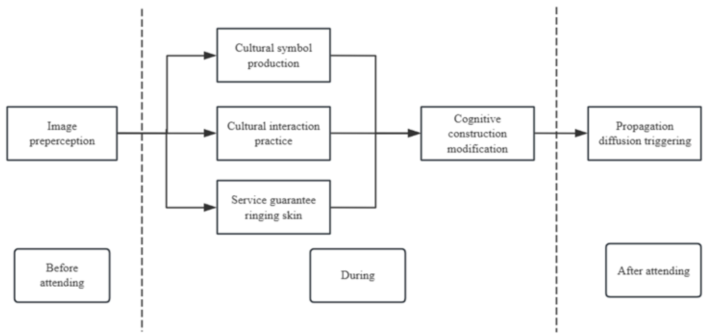

Figure 1. City image model of Music festival

The current main category system has formed a static network structure of actors, but its dynamic operation has not been clearly explained. This paper studies the four translation links introduced into ANT, namely problematization, benefit conferring, recruitment and mobilization, to transform the main category into a dynamic network operation unit. The key problem that the network must solve is that the music festival needs to transform the traffic attraction (star/social media) into cultural recognition through the local production of symbolized experience, and thus coordinate the interests of multiple actors. First, cities need to transform traditional culture into acceptable expressions for young people through music festivals, thereby transforming cultural capital into communication effectiveness. Second, cities provide venues and institutional resources to music festivals in exchange for participants' dissemination of the city's image, while music festivals attract participants to participate in the expression and dissemination of culture through innovative scene rules. Eventually, this master category system maps into a heterogeneous network of human and non-human actors, as shown in Figure 2.

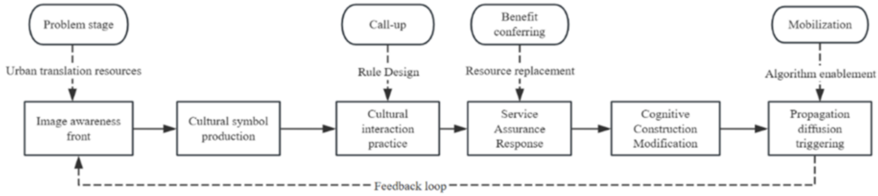

Figure2. Dynamic model of music festival propagation city image

Table 4 illustrates the interaction of actors in each category of the heterogeneous network. For example, the main category of cultural symbol production corresponds to the symbol authorization of the city to the music festival (the problem stage), while the main category of communication and diffusion triggering reflects the meaning reproduction of participants through the short video platform (the mobilization stage).

Table 4. Actor network Interactive network

Master Category	Actor network interaction
Image perception	City → Strawberry Festival → Participants (problem stage)
Cultural symbol production	City → Strawberry Festival → Participants (problem stage)
Cultural interaction practice	City ↔ Strawberry Festival → Participants (Call)
Service Assurance Response	City ↔ Strawberry Festival ↔ Participants
Cognitive Construction Revision	Participants → Strawberry Festival → City
Spread Trigger	Participants → Platform → Strawberry Festival, City (mobilization)

In Strawberry Music Festival's network of activists disseminating the image of the city, the participants, the festival itself and the city entity form a dynamic connection through a continuous process of translation. Through meaning negotiation, resource conversion and interest alliance, the three actors build a communication network of "cultural production, scene interaction and value diffusion", in which the music festival acts as the translation intermediary, the city provides distinctive cultural elements (such as intangible cultural heritage skills and dialect art), and the participants undertake the dual mission of cultural decoding and reproduction.

4. Strawberry Music Festival drives the coordination mechanism of heterogeneous actors in the transmission of city image

4.1 Strawberry Music Festival as the core actor: cultural translation center

Through the role of cultural translation center, Strawberry Music Festival transforms urban cultural resources into a symbol system that can be transmitted and experienced. In the image pre-perception stage, it activates the communication potential energy of the fan community through the star drainage strategy, and optimizes the hardware configuration such as traffic connection and health management by means of facility evaluation to build the dual cognition of "expectation-reliability". In the production process of cultural symbols, devices such as intangible cultural heritage workshop and dialect neon wall transform local culture into highly appealing visual symbols, while food cultural symbols realize the binding of "taste memory" and urban identity through local snack bars. Finally, the music festival scene is transformed into a super interface connecting the city's cultural capital and the young community.

4.2 Participants as key actors: content production networks and resistant practice subjects

Participants are deeply involved in the meaning contest of city image through UGC production and embodied practice. Based on strong relationship communication such as word-of-mouth recommendation from relatives and friends and support from fans, participants transform their individual interests into group actions, promoting the cracking spread of the popularity of the music festival. At the music festival site, ritualized behaviors such as 10,000 dialect chorus and exclusive hand gesture punch-in relay not only strengthened the temporary community identity among the participants, but also refined the embodied experience into a communication symbol carrying urban cultural genes through the positioning sharing of the circle of friends, short video challenge and other UGC content production. This change of identity from "bystander" to "co-creator" makes the emotional energy of the participants continue to feed back the brand value of the music festival, and triggers the secondary transmission of the city image by extending the tourism behavior. This kind of practice shows that participants are not only content nodes, but also conspirators and revisers of image narration.

4.3 Cities as fundamental actors: Infrastructure networks and cognitive correction toolkits

The local growth of music festival ecology is driven by the city's spatial governance ability and the supply of cultural resources. Through detailed operations such as traffic diversion and medical service points, cities transform their infrastructure advantages into a sense of perceived security, while measures such as free shuttle buses for night markets and the issuance of cultural travel guides highlight the city's strategic intention to incorporate music festivals into the regional tourism system. In the cultural dimension, the city reconstructs the participants' cognition through spatial narratives such as industrial heritage landmarks and new district construction achievements, and at the same time completes the youthful translation of traditional symbols with local cultural IP implantation. When the music festival becomes the showcase of the city's development level, the collaborative promotion between the cultural tourism department and the music festival will transform short-term activities into long-term brand assets, and realize the qualitative change from "cultural transfusion" to "value feeding".

4.4 Social media platforms as technical AIDS: relationship accelerators

Social media platforms reshape the space-time dimension of music festival communication through algorithmic logic and traffic rules. The reward mechanism of the Tiktok Challenge encourages participants to produce short video content with city positioning, while the Weibo hot search list penetrates through the topic of celebrity performances. The platform algorithm continues to excavate the nodes of high communication: artists' urban origin stories are pushed as emotional communication materials, while scenes such as dialect lamp sign photos and intangible cultural workshop experience are transformed into urban cultural promotion materials through LBS positioning. It extends the long tail effect of music festival communication, makes music festival break through the limitation of physical field, and completes the sustainable value exchange from city image to commercial flow in digital space.

5. Conclusion

5.1 Research Conclusions

Through the actor network theory, this study reveals the dynamic cooperative mechanism of strawberry music festival driving the urban image propagation. It is found that the construction of city image by cultural festivals is essentially a nonlinear interactive process between human and non-human actors through the translation network of "problematization, benefit conferring, recruitment and mobilization". Strawberry Music Festival, as the center of cultural translation, transforms the city's cultural capital into a perceptible scene of embodied experience, breaking through the limitation of one-way output of cultural symbols in traditional communication. Through UGC production, ritualized behavior and social media dissemination, participants become active subjects in decoding and re-encoding the city image. Their embodied practice not only reconstructs the cognitive correlation between "music festival and city", but also forms a feedback loop for correcting the city image through cross-platform content diffusion. Cities embed music festivals into local governance networks through infrastructure optimization and institutional resource supply to realize the continuous transformation of cultural capital into communication efficiency.

5.2 Management Implications

(1) Urban managers need to establish a translation mechanism between cultural resources and youth communities, transforming traditional symbols such as intangible cultural heritage and dialects into interactive experience scenarios. It is suggested to establish a cultural innovation laboratory, collaborating with curators and digital artists to develop immersive installations (such as AR check-in points for dialects and pop-up exhibitions of intangible cultural heritage workshops), and enhance cultural penetration through the process of "deconstruction - recombination - embedding". At the same time, a dynamic evaluation mechanism should be established to iterate the symbolic expression forms based on the preferences of Generation Z. For instance, a "retro-modern" themed exhibition area should be created by integrating local industrial heritage to continuously transform cultural capital into communication effectiveness.
(2) Build an elastic service system of "infrastructure - digital platform - emergency management". Adopt modular service units (mobile medical points, shuttle bus dispatching systems) to respond quickly to festival demands, and use big data to predict peak passenger flow and allocate resources. The key is to break down the data barriers among departments such as culture and tourism, transportation, and public security, and establish a smart command platform to achieve cross-departmental collaboration. Collaborate with social media to develop LBS push algorithms, implement traffic incentives for UGC content carrying city tags, synchronously monitor public opinion dynamics, and promptly optimize service shortcomings.

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Reaction of Iberian Stock Markets to the Distribution of Dividends: Efficiency Failure or Informational Failure?

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Abstract. The dividend distribution policy defined by managers is an important decision for corporate growth and for transmitting information to investors about the future of the business. This article analyzes the impact of dividend distribution announcements on the stock prices of companies listed on the Iberian indices (IBEX35 and PSI) between 2022 and 2023, using the event study methodology. 19 Portuguese and 21 Spanish companies were analyzed. The results show that investors in both markets anticipated dividends below expectations, given the formation of negative abnormal returns even before the distribution was announced. A few days after the announcement, the oscillation of average abnormal returns contracted, suggesting the advantages of diversifying investments in the Iberian markets. However, the significance of the effects does not disappear, suggesting evidence against the semi-strong form of market efficiency. It is therefore important to raise awareness among managers, investors and regulators of the usefulness of resources to support strategic financial decision-making based on digitalization and big data, and to strengthen financial literacy in society.

Keywords. Dividends; Event Study; Abnormal Returns; Price Reaction; Efficiency of Financial Markets.

1. Introduction

Financial markets are fundamental in modern economies for allocating resources between investors and finding the equilibrium value of assets based on available information. The concept of an efficient market, in different forms, was first defined by [1] and has been addressed in various fields of finance, particularly in the context of the events study. The transmission of new relevant information to the market can cause changes in the prices of financial assets. In this context, the announcement of a dividend distribution is new information that can send a signal about expectations of the future

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performance of companies [2]. The main objective of this article is to analyze the impact of dividend announcements on the stock returns of 40 companies listed on the Iberian markets - the IBEX35 index and the PSI index - between 2022 and 2023. Using the event study methodology, the analysis is carried out over the period [-5;+20] days. The conclusions point out that the Iberian markets are not yet fully mature, contrary to the semi-strong form of financial efficiency. Similar empirical evidence has been found in other studies of the same nature [3-9]. However, other authors have come to different conclusions regarding the impact of announcing dividends [10-13] justifying further research on the subject. It is therefore important to raise awareness among managers, investors and regulators of the usefulness of information systems in supporting strategic decision-making and their integration into education in order to strengthen financial literacy in society.

2. Literature Review

2.1 Financial Markets and Dividend Policy

The financial market is an essential foundation in the economy for the efficient allocation of resources. In this context, the stock market is the privileged means for buyers and sellers to trade company stocks [14]. Investors buy stocks in order to achieve a strategic position in a company or in the expectation of receiving returns that compensate for the risk of the investment [15]. This reward is received by the investor through dividends or capital appreciation. For this reason, managers are concerned with defining the ideal dividend policy to meet these expectations [16]. Dividends are part of corporate profits distributed in cash to the company's stockholders, in proportion to the number of stocks held, the policy of which depends on the need to retain profits for business reinvestment. The stock price includes public and private financial, social and management information available at a given time about companies [17]. In fact, dividends can provide signals about the company's situation, given that the distribution policy takes into account various factors, such as the company's need for funds, legal restrictions, future investment opportunities and borrowing capacity [15]. In this context, the signaling theory argues that companies use distribution policy to transmit signals (positive or negative) about future performance to the market, causing changes in stock prices [16]. The announcement of dividend distributions by companies has enormous relevance in the market and is of great importance in scientific financial research, where there is still no consensus on the subject. Some studies have pointed out that the announcement can cause significant changes in stock prices, resulting in abnormal returns due to investors' reaction to the new information [4-5], [8-9] [18-19], and limiting the arbitrage effect.

2.2 Semi-strong form of Financial Market Efficiency

Financial markets form a structured system where diversified securities are traded, with different levels of liquidity, risk and expected return. A market is considered efficient when asset prices reflect all the information available at the time [1] and [14]. In this context, all players have access to the historical price of assets and relevant information on the market. The efficient market hypothesis (EMH) exposes the market's adjustment to a price equilibrium resulting from new information, the conditions of which are contextualized by expectations of return on investment. According to [1], the sufficient conditions for an efficient market are: (1) no transaction costs for securities, (2) all players must have access to information free of charge and (3) all players agree on the effects of information on current asset prices and their future distributions (homogeneous expectations). According to the classification of [1], the semi-strong form of efficiency assumes that the stock price reflects the past behavior of returns and publicly available information. Later, [20] suggested the study of events as tests of this form of efficiency, in order to assess how quickly prices adjust to announcements and public information. A rapid adjustment suggests high market efficiency, reducing the opportunities for investors to make abnormal gains from exploiting this information.

2.3 Empirical Evidence on the Impact of Dividend Announcements

The authors [3] and [6] found that dividend policy has an effect on stock prices, constituting an information transmission mechanism. In addition, a dividend announcement generates a signal that causes stock price changes and can lead to abnormal returns [21]. The authors [9] also concluded that dividends influenced the stock prices of companies listed on the Colombo Stock Exchange (CSE). However, the empirical evidence on the impact of the distribution announcement is still far from unanimous. In an event study conducted on the Muscat Stock Market, [19] found a significant increase in stock prices on the second day after the date of the dividend distribution announcement. The work of [22] showed a significant reaction in the share prices of the Center for Research in Security Prices (CRSP) around the date of the dividend announcement. During a period of slow growth, slightly positive abnormal returns accumulated up to 3 days after the event. The authors [8] also found that the announcement had an immediate effect on the stock prices of the Dhaka Stock Exchange index (DSE30). Looking at the Indian market, [4] detected average abnormal returns on the day of the announcement and various changes in the cumulative average abnormal returns. Studying the behavior of stock prices after the announcement on the Bovespa, [18] identified higher cumulative abnormal returns in the companies that distributed the most. The authors [23] also argued that the announcement of dividend increases does not have a significant effect on the cumulative abnormal returns of the FTSE 350 index, in contrast to the announcement of dividend decreases during seasonality periods. On the other hand, [5] found a negative relationship between the announcement of the distribution and abnormal returns on the Indian National Stoch Exchange (NSE). Furthermore, some authors concluded that the announcement had no impact on stock returns, such as [10] and [13] on the Indian Stock Exchange, [12] on the Karachi Stock Exchange (KSE), and [11] on the New York Stock Exchange, supporting the semi-strong form of EMH. Meanwhile, [7] found evidence of inefficiency in the Gulf Cooperation Council (GCC) market due to information leakage before bad news announcements and delayed price adjustments in the face of good news. Khan [12] had also reported evidence of information leakage through the discovery of significant unexpected returns two days before dividend announcements.

3. Methodology

3.1 Event Study

The methodology underlying the events study makes it possible to eliminate general economic conditions and differences in the risk and return of companies in order to properly analyze the phenomenon [24]. The procedure uses the abnormal returns impacted during the event window, calculated by the difference between the observed return (caused by the event) and the expected return (determined by the market model). This methodology is ideal for assessing discrepancies between actual stock returns and their estimates in the days surrounding the event [25]. From a short-term perspective, this article's approach is based on the hypothesis that the announcement of a dividend distribution represents new information for the market, implying changes in investor expectations about the companies involved, with a consequent impact on stock prices. Initially, it is important to identify the event and then define the analysis interval, the estimation window and the event window [26]. The event corresponds to the announcement of the distribution of dividends by the companies in the sample. The analysis interval consists of the period of time before and after the event defined by $[-x; 0;+y]$, where x is the number of days before the date (t=0) of the event and y is the number of days after. During the previous days it will be possible to capture any information leaks to the market and during the subsequent days it will be possible to identify any impacts of the event. The observed (normal) returns are calculated in the estimation window of $[-x;-x_1]$ days, and the abnormal returns are calculated in the event window of $[-x_2;+y]$ days. The separation between the estimation window and the event window is intended to ensure that the normal returns are not influenced by new information around the date of the event, the possible impact of which will be reflected in the abnormal returns.

3.2 Abnormal Returns

Abnormal returns are calculated by the difference between the observed stock returns and their expected normal returns [26] and [27]:

$$AR_{i,t} = R_{i,t} - E(R_{i,t}|X_t) \tag{1}$$

where $R_{i,t}$ are the observed returns of the stock i on the day t and $E(Ri,t|Xt)$ are the expected returns conditioned by the information X_t. In turn, the daily observed returns are calculated by the Neperian logarithm of the quotient between the closing prices on consecutive trading dates. The normal expected returns are estimated using the linear regression of the market model:

$$E(R_{i,t}|X_t) = a_i + \beta_i \, R_{m,t} + \varepsilon_{i,t} \tag{2}$$

where $R_{m,t}$ is the observed return of the market index on the day t and $\varepsilon_{i,t}$ is the residual random variable, being $E(\varepsilon_{i,t})$=0 and $Var(\varepsilon_{i,t})$=σ^2. In addition, α_i and β_i are parameters of the regression model, where the former represents the stock return independent of the market return and the latter represents a measure of the stock's sensitivity to marginal market fluctuations, both calculated by the ordinary least squares (OLS) method for each company in the respective estimation window.

Conceptually, the $\varepsilon_{i,t}$ component is specific to the company, related to intrinsic information that reaches the market. In the case of this article, the new information consists of the announcement of a dividend distribution that could have an impact on stock prices in the form of daily abnormal returns for the event window:

$$AR_{i,t} = R_{i,t} - \left(\hat{a} + \widehat{\beta_i}\, R_{m,t}\right) \tag{3}$$

Under the null hypothesis that the event has no impact on stock returns, the distributional properties of $AR_{i,t}$ can be used to make inferences in any period of the event window, assuming that $AR_{i,t} \sim N\ [0\ ,\ \sigma^2(AR_{i,t})]$. To increase the usefulness of the isolated procedure, the AR of individual stocks are incorporated through the average abnormal returns (AAR) of N events for a period t, and the hypothesis test is carried out using the estimator:

$$\theta_1 = \frac{AAR_t}{\sqrt{Var(AAR_t)}} \sim N(0;1) \tag{4}$$

The accumulation of abnormal returns makes it possible to draw general inferences for the event of interest, and should be carried out under the dimensions over time and between stocks. The concept of cumulative average abnormal return (CAAR) is necessary to accommodate a multi-period event window between t_1 and t_2. Once again, under the null hypothesis that the event has no impact on stock returns, the distributional properties can be used, assuming that $CAAR(t_1, t_2) \sim N[0\ ;Var(CAAR(t_1, t_2))]$, and the hypothesis test is carried out using the estimator:

$$\theta_2 = \frac{CAAR_{(t_1,t_2)}}{\sqrt{Var\left(CAAR_{(t_1,t_2)}\right)}} \sim N(0;1) \tag{5}$$

In addition, the empirical work calculates the intensity of the reaction of AR to the announcement of the Covid-19 pandemic, using the ratio from [28]:

$$R = \frac{AR_{i,t}^2}{\sigma_{\varepsilon,i}^2} \tag{6}$$

where $\sigma_{\varepsilon,i}^2$ is the variance of the residuals calculated in the estimation window.

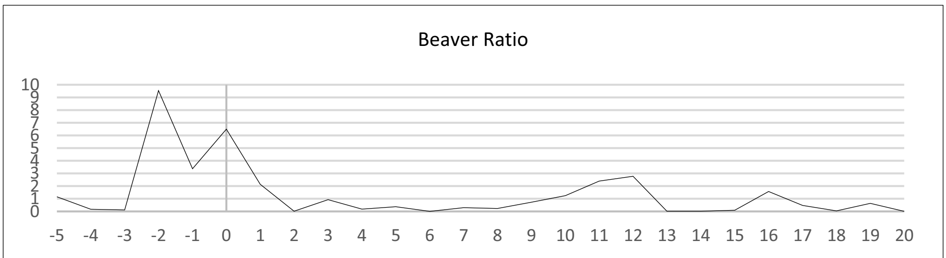
4. Empirical Study

4.1 Sample, Data and Analysis Period

The empirical study uses the daily closing stock price of companies listed on the main stock market indices in the Iberian market - the Iberia Index (IBEX35) and the Portuguese Stock Exchange (PSI) - during the years 2022 and 2023. In total, the sample includes 40 companies, 19 based in Portugal and 21 in Spain. In order to analyze the impact of the announcement of dividend distribution on stock prices, in the search for abnormal returns, the event study procedure considers the estimation window [-90;-30] days and the event window [-5;+20] days, taking into account the date (t=0) of the dividend announcement that characterizes the event.

4.2 Results and Discussion

The paper aggregates the results of 40 Portuguese and Spanish companies, listed on the Iberian indices, which announced dividend distributions during the period under analysis. Graph 1 shows the aggregate stock price reaction of the companies listed on the Iberian indices, as measured by the Beaver indicator, and Table 1 presents the results of the two-sided θ1 hypothesis test for the statistical significance of the aggregate AAR over the period [-5;+20] days.



Graph 1 - Stock Price Reaction: [-5; +20] days

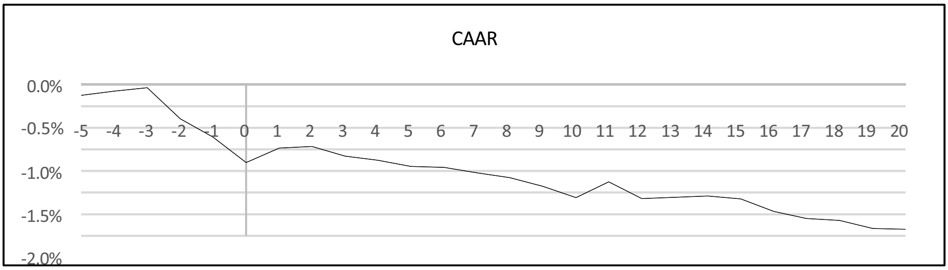
Table 1 - Hypothesis Test θ1 on Average Abnormal Returns (AAR): [-5;+20] days

-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9	+10	+11	+12	+13	+14	+15	+16	+17	+18	+19	+20
-1,1	0,4	0,4	**-3,2**	-1,9	**-2,7**	1,5	0,2	-1,0	-0,4	-0,6	-0,1	-0,6	-0,5	-0,9	-1,2	1,6	-1,7	0,1	0,1	-0,3	-1,3	-0,7	-0,2	-0,8	-0,1

Note: the first line indicates the days and the second line indicates the p-values (bold indicates significant at 5%)

The configuration of graph 1 identifies significant peaks on days t=-2 and t=0, both formed by negative AARs. This suggests that the market discounted the fall in expectations of a generous dividend distribution the day before the event, which was confirmed with the announcement. After the practically horizontal low-amplitude movement between days t=+2 and t=+9, there were some replicas at t=+11, with gains, and at t=+12 and t=+16, with losses, although they were not statistically significant.

Graph 2 shows the evolution of the aggregate CAAR of the companies listed in the Iberian indices and table 2 shows the results of the hypothesis test $\theta 2$ bilateral for the respective statistical significance during the period [-5;+20] days



Graph 2 - Cumulative Average Abnormal Returns (CAAR): [-5; +20] days

Table 2 - Hypothesis Test θ2 on Cumulative Average Abnormal Returns: [-5;+20] days

-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9	+10	+11	+12	+13	+14	+15	+16	+17	+18	+19	+20
-0,2	-0,1	-0,1	-0,6	-0,9	-1,4	-1,1	-1,1	-1,3	-1,4	-1,5	-1,5	-1,6	-1,7	-1,8	**-2,0**	-1,7	**-2,0**	**-2,0**	**-2,0**	**-2,0**	**-2,3**	**-2,4**	**-2,4**	**-2,6**	**-2,6**

Note: the first line indicates the days and the second line indicates the p-values (bold indicates significant at 5%)

Corroborating the previous evidence, graph 2 shows an accumulation of negative AAR, with three downward moments: the first was more pronounced in the three days up to the date of the event, the second from day t=+2 and the third from day t=+15. During the analysis period, there were two slight recoveries, one in the two days following the event and the other on day t=+11. However, the significant negative performance from day t=+10 onwards led to the accumulation of abnormal losses of -3.35% by the end of the analysis period.

5. Conclusion

The main objective of this article was to analyze the impact of the announcement of dividend distribution on the stock returns of 40 companies listed on the Iberian indices during the period 2022 to 2023. Using the event study methodology, the work was carried out over the interval [-5;+20] days. The results show a tendency for negative AARs to accumulate before the event, suggesting that investors pessimistically anticipated the dividends released by the companies in the sample. In addition, there was a significant negative reaction in stock prices on day t=0, showing that the dividend announcement had an impact on stock prices. After the narrower period around the announcement date, the oscillation of the joint AARs contracted, suggesting the advantages of diversifying investments in the Iberian market. However, the accumulation of significant losses from day t=+10 onwards provides evidence against the semi-strong form of financial efficiency. This evidence means that the Iberian markets are not yet fully mature.

It is therefore important to make managers, investors and regulators aware of the usefulness of resources to support strategic decision-making, such as digitalization and big data in finance. The efficiency of markets depends on the quality of information and the speed of its transmission, which can be improved by new technologies. This may mitigate the potential information leakage problem associated with identifying significant abnormal returns a few days before the dividend announcement, thus contributing to a better understanding of the theory. In practical terms, there is a need for continuous monitoring of the functioning of the market and for agile regulatory intervention that can benefit from the capabilities of new technologies. Finally, the support from information management systems should be integrated into education to benefit the strengthening of financial literacy in society.

For future work, we propose to deepen the research through a segmented analysis by independent market and by sector of activity, in search of response profiles to the dividend announcement and proximity to the EMH.

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Modern Management based on Big Data VI
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Analysis of Industrial Product Quality and Safety Supervision from Point to Surface

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Abstract. This paper explores the path of industrial product quality and safety supervision from "point" to "surface," taking the problematic products and enterprises discovered in supervision as the entry point to identify associated and similar risks. The study excavates key factors influencing quality and safety from the perspectives of supply chains and corporate investment and operation, establishes a quality risk relationship transmission network model (quality relationship network model), and uses big data, artificial intelligence technologies (such as community detection algorithms) to estimate the probability distribution of hidden quality states through limited risk point clues. This realizes the measurement of quality risk correlation between industrial products and enterprises, clarifies the risk association degree and impact degree between identified risk points and industrial products/enterprises to be discovered, and further analyzes risk transmission paths. Different from traditional quality supervision, which discovers isolated quality risk points through methods such as quality sampling and public opinion risk monitoring, supervision based on the quality relationship network constructs networks from two dimensions: supply chains and investment operations. Through this network, it identifies and locates enterprises and products with highly correlated quality risks, achieves cross-product type, cross-enterprise type, and cross-regional quality risk identification, and promotes the leap of quality supervision from "point" to "surface," enhancing supervision coverage. Additionally, the paper proposes suggestions such as accelerating the interconnection and interoperability of supervision data and improving the efficiency of quality and safety risk management through AI research and development based on the research content.

Keywords. Quality Relationship Network, Quality and Safety Risk, Supply Chain, Corporate Operational and Investment Relationships

1. Introduction

1.1. Research Background

In the supply chain environment, the entire process of industrial products from production to after-sales service requires the joint completion of member enterprises in the supply chain network. Objectively, industrial product quality is guaranteed and realized by all members of the supply chain network, meaning the formation and realization process of industrial product quality is actually distributed throughout the supply chain [1][2]. Quality management for supply chains should expand the scope of

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consideration from single enterprises to multiple enterprises and emphasize collaborative quality management among enterprises. For example, the spool component in a faucet of a manufacturer was found to be unqualified during the supervision and sampling inspection, which may be due to the use of inferior materials by the upstream parts assembly plant in addition to the manufacturer itself. In the business and investment relationship between enterprises, it is also very likely that they share the same supply chain, or have the same business management philosophy, quality control methods and other important factors affecting product quality. For example, if a non-conforming valve core component is found in a faucet produced by an enterprise during supervision and sampling, the cause may not only lie with the production enterprise itself but also with upstream component manufacturers using inferior materials. In the operational and investment relationships between enterprises, there is a high likelihood of sharing supply chains or having identical management concepts and quality control methods that influence product quality[3] [4] [5] [6] [7]. For instance, investors with high equity shares hold significant decision-making power in enterprises, exerting substantial influence on daily operations such as ensuring product quality and safety and carrying out quality upgrades; different enterprises invested by the same investor have a certain degree of correlation in product quality and safety risks. Relationship networks that may transmit quality risks, such as supply chains and corporate operations/investments, are referred to as quality relationship networks in this paper.

Traditional industrial product quality and safety supervision mainly focuses on relatively isolated risk points, with insufficient in-depth research on mining other potential risk correlations from identified problematic products and enterprises and analyzing risk transmission paths[8]. To maximize the value of limited and precious regulatory data from product quality safety supervision sampling and special rectifications and improve the comprehensiveness and accuracy of identifying and locating potential risk points, this paper proposes constructing a theoretical model for industrial product quality and safety supervision from point to surface. Taking problematic products and enterprises discovered in supervision as the entry point, it identifies associated and similar risks, excavates key factors influencing quality and safety from supply chain and corporate investment/operation dimensions using big data, AI, and other technologies, and establishes a quality risk relationship transmission network model (quality relationship network model). This model identifies and constructs the correlation degree of industrial product enterprises in supply chains and the relevance of different enterprises in equity investment, product research and development, and operations, ultimately achieving the measurement of quality risk correlation between industrial products and enterprises through analysis and evaluation of the above relationships [9] [10]. It determines the risk association degree and impact degree between identified risk points and industrial products/enterprises to be discovered, analyzes risk transmission paths, identifies regional and industrial product quality and safety issues, realizes point-to-surface management of industrial product quality and safety, and achieves early detection, early analysis, early warning, and early disposal of quality and safety risks.

1.2. Key Research Questions

On the basis of in-depth analysis of quality inspection data and preliminary identification of potential risk points, a supplementary enterprise quality relationship network is constructed from the perspectives of product supply chain, enterprise investment, and operation, to measure the quality risk correlation between industrial products and enterprises, improve the regulatory coverage of enterprises and products, and discover potential key risk points for industrial product regulation. Provide support for precise supervision.

Compared with traditional quality supervision that discovers isolated quality risk points through quality spot checks, public opinion risk monitoring, and other methods, supervision based on quality relationship networks constructs a quality relationship network from the supply chain and investment operation levels, and discovers and locates enterprises and products with high correlation in quality risks through the quality relationship network. This can achieve quality risk identification across product types, enterprise types, and regions, explore the transition from "point" to "surface" quality supervision methods, and improve the regulatory coverage of enterprises and products.

1.3. Research Significance

Through this research, more risk information hidden behind supervision and public opinion data can be fully excavated, the correlation between products and related business entities can be deeply explored, and other enterprises and products with correlated quality risks can be identified and located. Compared with traditional methods of identifying and locating quality risks based on single-source quality supervision data, the method based on the industrial product quality relationship network model realizes a leap in quality management from "point" to "surface," which is of great significance for improving the supervision coverage of enterprises and products and implementing the main responsibility of enterprises for product quality and safety.

- Helping Enterprises Improve Quality and Efficiency

By focusing on key links in the upstream and downstream of industrial chains and establishing quality relationship networks based on product production and assembly links, this research helps enterprises accurately identify problem hazards in production, design, transportation, use, and other links, improve quality levels and production efficiency in all links, save enterprise production and operation costs, and effectively promote enterprise quality improvement, industry upgrading, and industrial efficiency enhancement. Additionally, scientific and detailed risk analysis and evaluation based on quality relationship networks can provide scientific basis for producers and distributors to understand quality information, optimize process quality management measures, save production and operation costs, and participate in market competition.

- Reasonable Allocation of Supervision Resources and Cost Saving by Identifying Quality and Safety Risks and Determining Supervision Priorities

Identifying and analyzing potential quality risks through quality relationship networks helps determine supervision priorities, including enterprises, products, and regions requiring key supervision, improving the fairness, precision, and effectiveness of quality and safety supervision, and saving supervision costs.

- Improving the Quality Level of the Entire Industry

Improving the coverage of enterprises and products through quality relationship networks and identifying potential key risk points can leverage small fulcrums to drive large-scale supervision and governance, addressing difficulties and "pain points" in industrial product safety supervision and providing in-depth and high-value information for governments at all levels and relevant departments to grasp the quality dynamics of various industries and enterprises. It also provides methodological support and data support for regulatory authorities to carry out targeted problem rectification and quality assistance. Furthermore, risk tracing based on quality relationship networks helps identify quality risk sources, driving industry-wide quality improvement through point-to-surface effects.

- Providing Data Support and Scientific Basis for Economic Macrocontrol and Policy Making

Through in-depth analysis of large amounts of data on raw materials, assembly, distribution, quality news, and consumer evaluations of key products, relevant data and analysis results are provided to decision-making departments. With the rapid development of new information technologies such as the Internet of Things, cloud computing, and mobile Internet, actively exploring research on industrial product quality and safety risk identification based on quality relationship networks and striving to overcome the drawbacks of "mass tactics" and "data silos" can achieve certain results in innovating supervision methods, improving supervision efficiency, optimizing the business environment, and assisting high-quality development. Meanwhile, the supervision method based on quality relationship networks can reduce potential safety hazards in industrial product production and operation and avoid regional and industrial product quality and safety incidents to a certain extent.

2. Literature Review

2.1. A study of product quality risk from a supply chain perspective.

In the research of product quality risk from the perspective of supply chain, some scholars at home and abroad have explored. Dudziak-Gajowiak (2019) [1], Wang Jinzhou (2021) [2] and other scholars analysed the quality risk from the perspective of supply chain, including the information difference of the supply chain's main bodies, the quality of the products of the suppliers, procurement, production process and other links, but did not analyse and research on the interaction between risk factors and the role of the mechanism are analysed and studied. There are also scholars such as Challinor AJ (2018) [11], Mo Junwen (2022) [12], Yao Hao (2021) [13] and other scholars have considered the mutual influence of the role of risk, and studied the cascade failure mechanism of risk and risk coupling mechanism and so on, but the application scope of the cascade failure and coupling mechanism is relatively limited.

2.2. A study of product quality risk under the network concept theory.

Some literature has made some research results by trying to introduce network-related concepts to study product quality risk, for example, Wang Jinzhou (2021) [2] and others constructed a multilevel complex product co-development network, studied the dynamic propagation process of quality risk in supply chain network, and obtained important quality risk control nodes; Li Tengjiao (2020) [14] and others constructed a complex network of supply chain and proposed a method for identifying key quality risk factors in the supply chain network based on the risk transfer effect. Li Tengjiao (2020) [14]and others constructed a complex supply chain network and proposed a key quality risk factor identification method based on risk transfer, which was applied to the study of quality risk transfer in the supply chain network of collaborative manufacturing of complex products; some scholars also put forward the theory of "Quality Chain" (2008), [15]but the interactive relationship, structural characteristics, and weights of each subject in the quality chain network have not yet been reflected. Generally speaking, the research content and methodology of applying network-related theories in the field of quality risk management are relatively single, and qualitative research is dominated by quantitative research. Some of the existing quantitative studies are also not deep enough to fully explore and make use of the quality-related big data that have been deposited, especially the regulatory data.

2.3. Research on the impact of business investment and operations on product quality.

In terms of the impact of enterprise investment and operation on product quality, the related literature discusses the impact of enterprise investment and operation strategies on product quality from different aspects such as enterprise technology innovation investment, enterprise R&D investment, and enterprise financing constraints.

With regard to the impact of enterprises' technological innovation input decisions on product quality, a large number of studies have shown that increasing enterprises' technological innovation efforts will enhance the quality of their products to a large extent.Motta (1992) [3], in analysing the impact of the level of technological innovation on product quality, found that the stronger the innovation capacity of the enterprise, the higher the quality of the output goods, and that when the enterprise invests more in innovation, the product quality of the enterprise is also higher. Faruq's (2010) [4] empirical analysis based on US import data shows that technological innovation significantly improves product quality. Luo Liying et al. (2016) [5] found in their study of the impact of technological innovation on product quality that enterprises improve the level of technological innovation, can accelerate the speed of updating and upgrading machinery and equipment and improve hardware facilities and equipment, and promote the optimisation and improvement of product structure, which is conducive to improving product quality. Shi Bingzhan (2014) [6], in the process of measuring product quality, found that factors such as R&D efficiency and R&D investment have an impact on product quality, but the effect of R&D efficiency on product quality improvement is greater than that of R&D investment. Zheng Lei et al. (2020) [7] found that technological innovation can improve both enterprise competitiveness and product quality.

Existing literature on the impact of firms' investment and business behaviour on product quality mostly uses indicators such as firm competitiveness, product sales and exports to indirectly measure product quality, but does not directly use quality indicators to explore product quality from the perspective of firms' investment and business. Different implementation strategies of enterprise investment and operation may have different effects on product quality, such as stable investment and supply relationship can help establish long-term partners, and promote suppliers to pay attention to quality and continuous improvement; based on the common interests of investors and suppliers in quality, through cooperation can work together to ensure product quality and safety; reliable investment and supply relationship can ensure the stable supply of raw materials and components, and avoid supply disruption. A reliable investment and supply relationship can ensure the stable supply of raw materials and components, and avoid the impact of product quality due to supply disruption. Therefore, it is worthwhile to further explore the impact on product quality from the perspective of enterprise investment and operation.

Through combing and reviewing the above literature, this paper finds that academia has conducted some theoretical research and empirical analysis on the impact of supply chains, corporate investment, and operational relationships on product quality and attempted to introduce network-related concepts to explore product quality risk influencing factors and transmission mechanisms. Based on previous research, this paper fully absorbs the rich research achievements of domestic and foreign scholars. On the basis of in-depth analysis of quality supervision data and public opinion information and preliminary identification of potential risk points, it supplements and constructs enterprise quality relationship networks from product supply chains and corporate investment/operations dimensions, realizes the measurement of quality risk correlation between industrial products and enterprises, identifies other enterprises and products potentially correlated with quality and safety risks through quality relationship networks, scientifically identifies the quality and safety risk levels of related enterprises and products, facilitates analysis of internal source risk points, analyzes risk transmission paths, explores and discovers regional and industrial product quality and safety issues, and realizes point-to-surface management of industrial product quality and safety.

3. Analysis of Industrial Product Quality and Safety Supervision from Point to Surface

3.1. Supervision of Product Quality and Safety, Integration of Public Opinion Data, and Identification of Risk Clues

Technologies such as big data mining are used to identify problematic products and enterprises, uncovering clues to potential risk points and providing a foundation for subsequent model construction. Regulatory data is collected from sources including random inspections, production licensing, and compulsory product certification, as well as from various supervisory activities conducted by market regulatory authorities at all levels—such as routine inspections, surprise inspections, and random checks. Additionally, information from risk monitoring, public opinion monitoring, and commissioned testing carried out by technical institutions under the organization of regulatory authorities is gathered and organized to locate problematic products and enterprises. Public opinion data related to quality and safety is characterized by rapid updates, timely feedback, and broad coverage, and can serve as an important supplement to traditional regulatory methods [16].

3.2. Construction of a network model of industrial quality relationships in enterprises.

Each link in the supply chain and each basic element in the enterprise investment and operation network corresponds to a corresponding quality risk (i.e., a hidden quality state). The quality relationship network of enterprise industrial products (as shown in the figure below) is to achieve the analysis and identification of the transmission mechanism of quality risk among different links, products and enterprises by modelling the visible states of the product supply chain, enterprise investment and operation levels, and by analyzing and predicting the above network model in order to estimate the probability distribution of the hidden quality states. Therefore, the quality relationship network provides a method for effective analysis and prediction of potential quality risks that cannot be directly observed, and provides a theoretical basis for quality management from "point" to "surface", and for exploring and analysing regional and industrial product quality and safety problems. Theoretical basis [17].

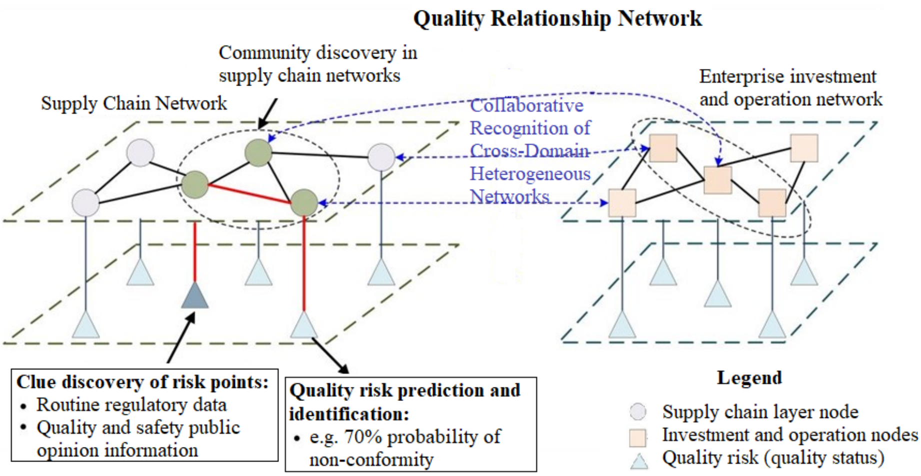

Figure 1. Schematic diagram of the quality relationship network.

According to the many relationships such as chronological relationship, correlation relationship and causality relationship that affect product quality, we construct a more complete enterprise quality relationship network from two levels of product supply chain and enterprise investment and operation, and study to estimate the probability distribution of the hidden quality state by using the limited risk point clues that have been obtained, and finally realise the analysis and identification of the transmission mechanism of quality risk in different links, different products and different enterprises.

Supply chain network. Firstly, based on the product classification rules and historical data of product quality supervision, the correlation between products is studied, and the product database data is used to establish a relationship network formed by expanding outward layer by layer, with the upstream and downstream enterprises of the industrial chain of the identified clue products and their finished products as the core [18] [19]. Among them, each link in the supply chain corresponds to the corresponding quality risk (i.e., hidden quality state), thus forming an industrial product quality network with supply chain relationship as the observable state and quality risk as the hidden state.

Enterprise investment and operation network. The study makes use of the investment and equity relationships, director and executive relationships, patent development and citation relationships, as well as litigation and bidding relationships among different enterprises to establish a relationship network formed by taking the investment and operation relationships of the enterprises related to the identified clue products as the core, and expanding outward layer by layer. Each basic element in the network corresponds to a corresponding quality risk (i.e., a hidden quality state), thus forming an industrial product quality network with investment and business relationships as observable states and quality risks as hidden states [20]. The network analyses and predicts the transmission mechanism of quality risk among different products and enterprises by comprehensively exploring various correlations and similarities in the investment and operation activities of enterprises [21].

Aspects of quality risk prediction based on community discovery algorithms. The concept of community comes from social networks, which refers to the decomposition and division of social networks in terms of structure [22]. "Community discovery" refers to the use of effective methods to mine and identify the potential communities in the network, which is an important technical approach to study the network structure. Generally speaking, there are indeed tightly connected communities in a quality relational network, i.e., intra-community connections are basically strong connections, while inter-community connections are weak connections. Community discovery algorithms are meant to identify these communities (as shown in Figure 2), and the transfer of quality risk is biased towards taking place within communities. By performing community discovery on the quality relationship network, we can analyse the structure of the network, calculate the quality risk of each node, and find the core nodes that influence the transmission of quality risk

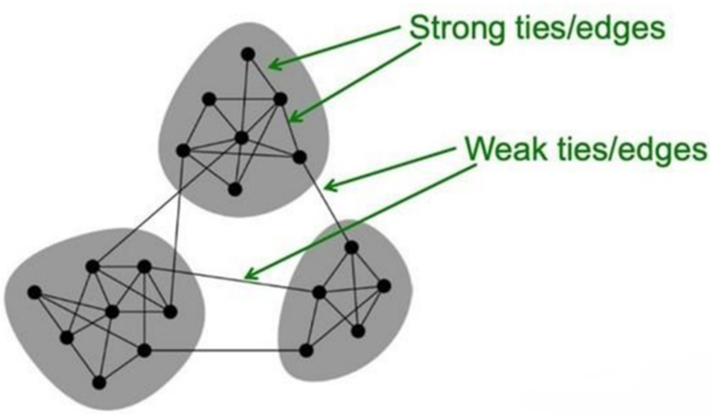

Figure 2. Schematic of community discovery.

The study uses community discovery algorithms to analyse and discover clusters of nodes that are strongly connected and close to each other in the quality relationship network, and investigates the construction of a quality risk measurement model based on the distance between nodes. Specifically, the existing routine regulatory data and quality public opinion information are first analysed in order to identify the initial quality risk points; then the community discovery algorithm is used to identify clusters of nodes in the quality relationship network that are strongly connected to the identified risk points; and finally, the probability of quality risk is measured based on the distance between nodes.

3.3. Case study calibration.

Industrial products with numerous quality and safety performance indicators—such as electric bicycles and indoor heaters—are selected as case studies for quality risk prediction and identification using the quality relationship network model. By analyzing regulatory data and public opinion information, non-compliant manufacturers and substandard product items can be identified. For example, if regulatory authorities discover that the charger and battery of an electric bicycle produced by Company A in a certain region fail to meet quality standards (the initial quality risk point), upstream Company B—responsible for supplying batteries or raw materials—can be identified through databases and publicly available information. Further connections can be traced to other enterprises in Company B's supply chain network. Clustering and community detection algorithms can then be applied along the component or material supply pathways to assess the quality status of industrial products produced by these related companies.

On the other hand, using information from litigation records, bidding activities, and patent applications, enterprises with investment relationships to Company A can be identified and mapped to related entities (the corporate investment and operation network). Clustering and community detection algorithms are used to analyze investment proportions and infer the extent to which business decisions influence product quality, thereby helping locate other potentially risky products.

By employing clustering and community detection algorithms, closely connected and "proximal" node clusters within both networks (i.e., the supply chain network and the corporate investment-operation network) can be identified. It is assumed that the transmission of quality risk is negatively correlated with the "distance" between nodes—meaning that the closer and more tightly connected two nodes are, the more likely they are to simultaneously exhibit quality issues. Hence, a risk measurement model based on inter-node "distance" is studied.

Specifically, the process involves:

- Analyzing existing regulatory data and public opinion feedback to identify an initial quality risk point A;
- Utilizing limited clues—such as component supply paths or investment ratios related to decision-making—to identify clusters of nodes in both networks that are closely linked and in proximity to the known risk point, using clustering and community detection algorithms;
- Estimating the probability of quality risks based on the "distance" between nodes, where nodes closer to the known risk point are considered to have higher likelihoods of associated quality risks.

In summary, based on various relationships that influence product quality—including temporal sequences, associations, and causality—this study constructs a comprehensive enterprise quality relationship network from both supply chain and corporate investment-operation perspectives. By leveraging limited risk clues to estimate the probability distribution of hidden quality states, the model ultimately facilitates analysis and identification of how quality risks are transmitted across different stages, products, and enterprises.

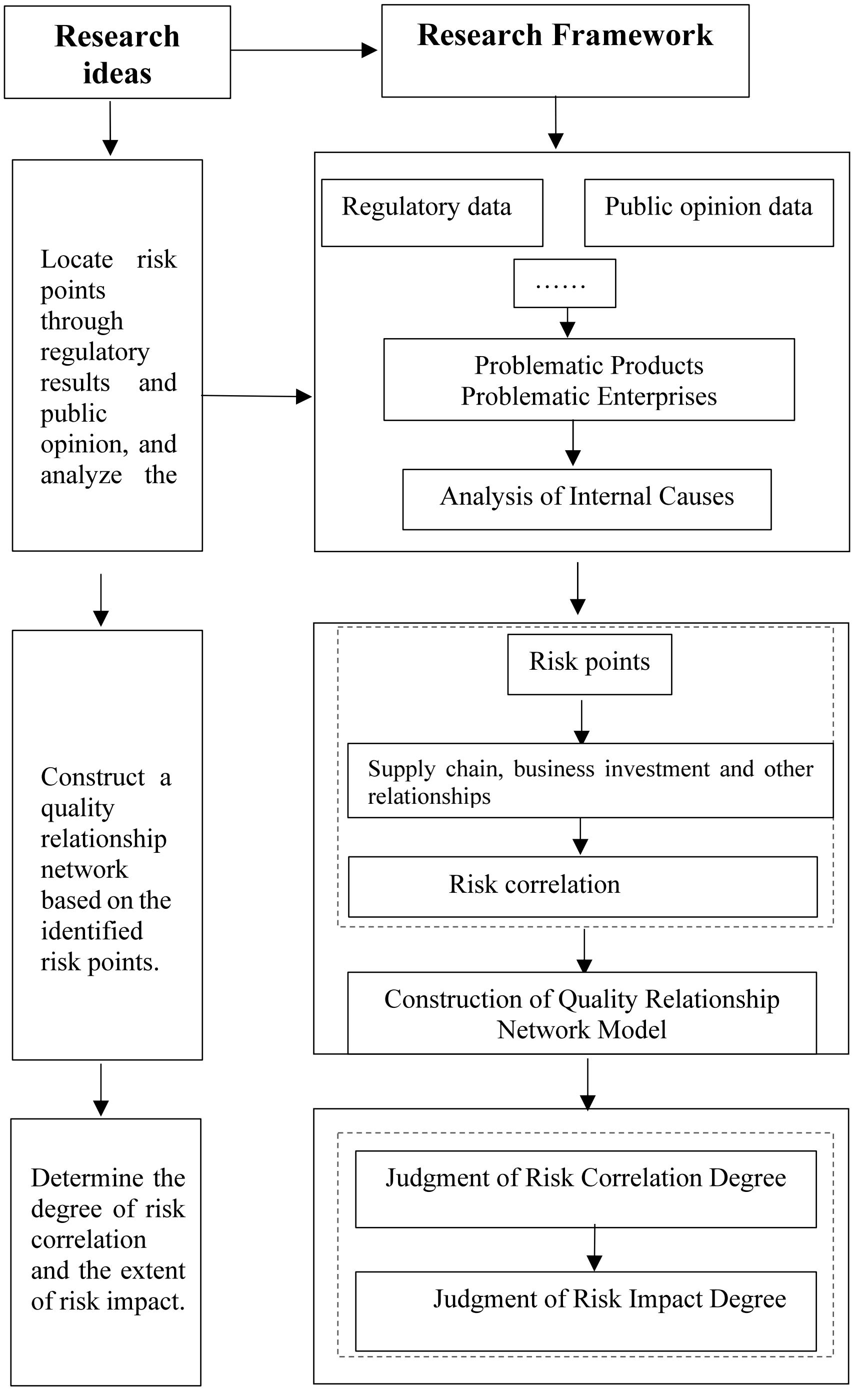

Figure 3. Technical Route Flowchart.

3.4. Key issues to be addressed

- Theoretical Novelty

This project treats industrial product quality as a hidden state that cannot be directly observed and considers supply chain factors and corporate investment/operation factors as observable states closely linked to quality states, thereby modeling the transmission relationships between observable states to analyze and identify hidden quality states. This approach of analyzing and modeling various observable states closely related to industrial product quality provides a new theoretical perspective and solution for identifying hidden quality states. The quality relationship network constructed in this project offers a methodology for effectively identifying and predicting potential quality risks that cannot be directly observed, providing a theoretical basis and methodological support for predicting and identifying quality risk transmission across different links, products, and enterprises.

- Technical Interdisciplinarity

This project combines relevant theories, knowledge, and experience in the field of industrial product quality supervision with big data mining and artificial intelligence technologies, aiming to empower precise supervision and improve quality supervision efficiency through big data accumulated in the quality supervision field. The technical interdisciplinarity of this project is mainly reflected in: introducing the concepts of "community" and "community detection" into quality relationship networks; applying semantic network technology to the intelligent extraction and reasoning of quality public opinion data; and applying heterogeneous network analysis theories to cross-domain quality risk collaborative identification.

- Application Innovation

Compared with traditional quality supervision, which discovers isolated quality risk points through methods such as quality sampling and public opinion risk monitoring, supervision based on quality relationship networks constructs relationship networks from two dimensions: supply chains and investment operations, and discovers and locates enterprises and products with highly correlated quality risks through these networks. Therefore, applying quality relationship networks can achieve cross-product type, cross-enterprise type, and cross-regional quality risk identification, explore the leap of quality supervision methods from "point" to "surface," and improve the supervision coverage of enterprises and products. Compared with traditional quality supervision, which discovers isolated quality risk points through methods such as quality sampling and public opinion risk monitoring, supervision based on quality relationship networks constructs relationship networks from two dimensions: supply chains and investment operations, and discovers and locates enterprises and products with highly correlated quality risks through these networks, enabling cross-product type, cross-enterprise type, and cross-regional quality risk identification, exploring the leap of quality supervision methods from "point" to "surface," and improving the supervision coverage of enterprises and products.

4. Data and artificial intelligence: elements for exploration and practice.

In the exploration and practice of the theoretical approach to quality and safety risk management from point to point, "data" is the basic element and "artificial intelligence" is the efficiency element. Recommendation:

4.1. Accelerating the interconnection of regulatory data.

Accelerating the interconnection of regulatory data, improving the real-time and sensitivity of information and data, and serving the needs of actual combat. Strengthen data governance, enhance the credible traceability of data and the ability to verify and correct errors, and improve data quality. Actively broaden the source channels of risk information, and achieve docking with 12365, 12315 complaint and reporting system, CC complaint and counselling information system, and product injury monitoring system. Jointly with the Ministry of Transport, the Ministry of Public Security, the Health Commission and other relevant departments to achieve the sharing of information. Deeply promoting the construction of consumer product quality and safety risk information monitoring points, effectively uniting various resources to form a national chessboard. Integrate existing risk information resources, make use of "big data" technology, discover and closely track sensitive information on quality and safety in a timely manner, strengthen the integration and integrated analysis of risk information, and improve the level of interactive application of risk data.

4.2. Artificial intelligence research and development to improve the efficiency of quality and safety risk management.

Explore the use of artificial intelligence technologies, such as community discovery algorithms, to gradually establish a network relationship model for quality and safety risk transfer in the supply chain and enterprise investment and business relationships. Implement intelligent "cloud supervision" for the whole process of products, strengthen the analysis and application of big data of upstream and downstream production manufacturers of important industrial products, business platforms and supervision platforms, and use the research and development results as an important consideration for the quality assurance capability of enterprises and an important basis for carrying out precise supervision or assistance, so as to provide decision-making support for upgrading the modernisation of the industrial chain and supply chain, and promoting the healthy development of industries. Provide decision-making support for improving the modernisation level of the industrial chain supply chain and promoting the healthy development of the industry.

5. Conclusion

This paper explores a supervisory path for industrial product quality and safety that transitions from isolated “points” to an interconnected “network” perspective. Based on an in-depth analysis of product quality sampling data and preliminary identification of potential risk points, a quality relationship network for enterprises is constructed from two key dimensions: the product supply chain and corporate investment and operations.

This network enables the measurement of quality risk correlations between industrial products and enterprises, supports the scientific assessment of the subjects, objects, and characteristics of quality safety risks, and facilitates the extraction and interpretation of risk-related information. Consequently, it enhances regulatory coverage of enterprises and products and helps identify critical risk points in the industrial product supervision process.

The outcomes of this research are intended for application by market regulatory authorities, industrial production risk control departments at all levels, and various industrial product business entities. By providing decision-making suggestions or submitting advisory reports to relevant departments, the research aims to transform academic findings into “practical productivity.” This contributes to the procedural and intelligent transformation of market regulation work, enabling better product quality monitoring, improved regulatory precision, and enhanced decision-making support.

With the rapid advancement of emerging information technologies—such as the Internet of Things (IoT), cloud computing, and mobile internet—there is an urgent need to explore risk identification approaches based on quality relationship networks. This helps overcome the inefficiencies of “manpower-heavy” regulatory methods and data silos. Such innovations can significantly improve regulatory approaches, enhance regulatory efficiency, optimize the business environment, and support high-quality development. Furthermore, a quality relationship network-based regulatory model can help reduce potential safety risks in the production and operation of industrial products and, to some extent, prevent regional or industry-wide quality and safety incidents.

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Digital Transformation and Credit Supply in Commercial Banks - Based on Commercial Banks' Risk Taking Perspective

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Abstract: Based on the unbalanced panel data of Chinese commercial banks from 2014-2023, this paper empirically analyses the impact of commercial banks' digital transformation on credit supply and its mechanism of action from the perspective of risk-taking by using a two-way fixed effects model. It is found that the digital transformation of commercial banks significantly improves the level of credit supply, and this conclusion still holds after the robustness test. The mechanism test shows that commercial bank risk-taking plays a significant mediating effect between digital transformation and credit supply. The moderating effect test shows that digital financial inclusion negatively moderates the role of digital transformation on credit supply. The study suggests that commercial banks need to build dynamic risk buffer mechanisms to cope with technology spillovers, while regulators can guide classification governance through the construction of data sharing platforms. This paper provides an empirical basis for understanding the risk-return balance mechanism of technology-driven credit expansion.

Keywords: digital transformation; commercial banks; credit supply; risk taking

1. Introduction

With the deep penetration of financial technology, digital transformation is profoundly affecting the logic of bank credit decision-making by reshaping the risk control model and optimising service efficiency. However, there are still three theoretical propositions that need to be verified by the mechanism of digital transformation on credit supply. First, whether digital transformation directly enhances the level of credit supply through technological empowerment. Second, if there is an enhancement effect, whether risk-taking behaviour plays a key mediating role. Third, whether external competition for digital financial inclusion undermines the technological dividend of banks' digital transformation.

Currently, there are two main perspectives in academic research on digital transformation and credit supply: technology empowerment and risk alienation. On the

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one hand, the technology-enabling perspective emphasises that digital technology can enhance credit processing efficiency by optimising information processing (Hughes et al., 2022)[1] and mining unstructured data. Hou Sheng and Wang Lang (2024)[2]further point out that the digital transformation of banks increases the credit coverage of micro and small enterprises, which verifies the financial inclusion gain under the "long-tail effect". On the other hand, Fuster et al. (2019)[3]'s model extrapolation shows that algorithmic dependence leads to a decrease in the sensitivity of mortgage default risk, exacerbating the overinvestment of credit during economic downturns. Buchak et al. (2018)[4] find that digital technology is used to circumvent capital regulation, which contributes to an increase in the share of risky off-balance sheet credit. It can be seen that most of the existing studies focus on the direct effect or a single mechanism of digital transformation, and the study of risk-taking as a transmission hub between digital technology and credit business and its external condition constraints needs to be further explored.

The importance of this paper may be reflected in the following: firstly, this paper constructs an analytical framework from digital technology application to risk-taking to environmental regulation, providing a new theoretical perspective for parsing the dynamic response mechanism of technology-driven credit behaviour. Second, based on a sample of banks of different natures, this paper provides evidence for banks to develop differentiated transformation strategies. Third, by quantifying the intensity of the mediating effect of risk-taking and the direction of regulation of digital inclusive finance, this paper provides practical insights for commercial banks to balance technology-driven credit expansion and risk control, and provides certain references for regulators to formulate technology-adaptive regulatory policies.

2. Theory and assumptions

2.1 Digital transformation and credit supply in commercial banks

The digital transformation of commercial banks is profoundly changing the logic of traditional credit market operations through technological reconfiguration of credit business processes (Imerman et al., 2025)[5]. Under the traditional business framework, multiple factors constrain the credit supply capacity of commercial banks. On the one hand, information asymmetry leads to biased assessment of customer qualifications (Yan et al., 2015)[6]. On the other hand, the lengthy manual approval process and high-cost post-loan monitoring mechanism further compress profit margins. At the same time, strict capital regulatory requirements and conservative strategic orientation cause the lack of services in the long-tail market. The digital transformation of commercial banks provides a systematic solution to break through the above bottlenecks. Digital transformation builds a panoramic portrait of customers by integrating data from multiple sources and uses artificial intelligence algorithms to parse unstructured data to identify high-value customer groups (Yang Ting et al., 2025)[7]. Further, digital transformation can compress the credit decision cycle (Zhang et al. 2025)[8], and intelligent systems standardise processes to reduce human bias. Finally, digital transformation can enable banks to provide flexible adjustment space for resource allocation under the given constraints.

H1: Digital transformation of commercial banks can increase the level of credit supply of banks

2.2 The intermediary role of commercial bank risk-taking

The digital transformation of commercial banks systematically inhibits risk-taking by reconfiguring the risk decision-making mechanism. Firstly, digital transformation integrates multi-dimensional data to accurately identify potential risk signals to alleviate the problems caused by information asymmetry (Cao et al., 2022)[9], and reduces banks' risk-taking. Secondly, the non-tamperable fund flow records and real-time monitoring of collateral reduce moral hazard and enhance the efficiency of post-loan risk disposal (He Li et al., 2022)[10]. Finally, digital transformation inhibits irrational expansion of risk by responding to market fluctuations in real time (He Xiaogang, 2023)[11]. Reduced risk-taking by commercial banks drives robust growth in bank credit supply. On the one hand, the decline in bank risk-taking drives the concentration of credit resources to high-quality customers, which in turn optimises the credit structure and raises the level of supply. On the other hand, the reduction in bank risk-taking eases the pressure on asset quality and capital constraints and improves the elasticity of bank credit supply (Agénor & Silva, 2021)[12], which provides sustainable support for the expansion of credit resources.

H2: The digital transformation of commercial banks enhances bank credit supply by reducing bank risk taking

2.3 The moderating role of digital financial inclusion

The development of digital inclusion creates structural constraints on the credit supply effect of commercial banks' digital transformation. On the one hand, the marginal contribution of commercial banks' digital transformation may be diluted by the competitive effects of digital inclusive finance. Digital inclusive finance platforms divert long-tail customers by virtue of their low-threshold services (Han et al., 2025)[13], weakening the customer stickiness that banks have built through digitalisation. Its data aggregation and algorithmic matching form alternative credit networks, intensifying industry competition leading to diminishing marginal returns on banks' technology investment. In addition, the convenience and personalisation of digital inclusive finance reduce users' reliance on traditional channels (Yin Zhichao et al., 2024)[14]. On the other hand, the increase in the level of development of digital inclusive finance will further weaken the impact of digital transformation on the credit supply of commercial banks. Increased external competition and the prevalence of customers' multi-attribution behaviour combine to compress the scope for exclusive gains from banks' digital transformation (Cerasi et al., 2017)[15].

H3: The development of digital financial inclusion weakens the impact of digital transformation on commercial banks' credit supply

3. Research design

3.1 Sample selection and data sources

This paper selects 106 commercial banks in China from 2014 to 2023. They include 5 state-owned commercial banks, 12 joint-stock commercial banks, 75 urban commercial banks, and 14 rural commercial banks. The data are obtained from the Digital Finance

Research Centre of Peking University, Wind database and iFinD database, and supplemented by the annual reports of each bank. In order to ensure the data quality, the research samples are processed as follows:①Remove the missing samples of key variables.②Tailoring continuous variables at the 1% and 99% quantile. Finally, 1043 sample data were obtained.

3.2 Variable Measurement

(1) Explained variable: level of credit supply.This paper measures commercial bank loans divided by total assets.

(2) Explanatory variable: degree of digital transformation.This paper adopts the digital transformation index of commercial banks constructed by the Digital Finance Research Centre of Peking University as a measurement index.

(3) Intermediary variables: risk-taking.In this paper, the Z-Score value is selected to measure the risk taking of commercial banks. The specific calculation formula is shown in (1):

$$Z-Score_{i,t}=\frac{\sigma_i\left(ROA_{i,t}\right)}{ROA_{i,t}+SHE_{i,t}} \quad (1)$$

where $ROA_{i,t}$ is the return on total assets, $\sigma_i\left(ROA_{i,t}\right)$ is the rolling standard deviation of the bank's return on total assets every three periods, and $SHE_{i,t}$ is the share of equity assets. $Z-Score_{i,t}$ The larger the value, the greater the bank's default risk and the higher the risk-taking.

(4) Moderating variable: digital financial inclusion. This paper measures the level of digital inclusive finance development using the provincial-level digital inclusive finance index compiled by the Digital Finance Research Centre of Peking University, dividing it by 100 as empirical data.

(5) Control variables. In this paper, bank size, capital adequacy ratio, return on assets, cost-income ratio, GDP per capita, and GDP growth rate are selected as control variables, and the definitions of each variable are shown in Table 1.

Table 1 Definition of variables

variable name	variable symbol	define
Level of credit supply	Loan	Loans/total assets
Digital Transformation	Digital	1n (1+ digital transformation index)
risk-bearing	Z-Score	Level of commercial bank risk-taking
Digital Inclusive Finance	DFI	Digital Financial Inclusion Index divided by 100
Bank size	SIZE	Natural logarithm of total assets
capital adequacy ratio	CAR	Net capital/risk-weighted assets
return on assets	ROA	Net profit/average total assets
Cost-income ratio	CIR	Total operating costs/total revenue
GDP per capita	AGDP	Regional GDP/resident population in logarithms
GDP growth rate	GGDP	Year-on-year regional GDP growth rate

3.3 Modelling

This paper selects the fixed effect model by Hausman test (p=0.03).In order to verify the impact of digital transformation of commercial banks on the level of credit supply, this paper constructs the following benchmark regression model:

$$Loan_{i,t} = \alpha_0 + \alpha_1 Digital_{i,t} + \sum \alpha_m Con_{i,t} + \lambda_i + \lambda_t + \varepsilon^1_{i,t} \quad (2)$$

where i denotes the bank and t denotes the year; α_0 is the constant term of equation (2); $\alpha_1 \sim \alpha_m$ is the regression coefficient, where m=2...7; $Con_{i,t}$ is the set of control variables; λ_i and λ_t are the bank fixed effects and time fixed effects, respectively; and $\varepsilon^1_{i,t}$ is the random error term of equation (2).

4 Empirical analysis

4.1 Hypothesis testing

4.1.1 Direct effects test

A fixed effects regression analysis was used to run a progressive regression on equation (2). The regression results are shown in Table 2. where column (1) is the fixed effects controlling only for year and bank, the regression coefficient for digital transformation is significant at the 1% level as 0.0114. column (2) is the result of adding control variables to column (1), the regression coefficient for digital transformation is significant at the 1% level as 0.0156, and Hypothesis H1 is verified.

4.1.2 Tests for the mediating effect of commercial bank risk-taking

On the basis of equation (2), the stepwise regression method is used to construct a mediation effect model to analyse the role mechanism of risk-taking between digital transformation and credit supply, and the mediation effect model is shown below:

$$Z-Score_{i,t} = \beta_0 + \beta_1 Digital_{i,t} + \sum \beta_m Con_{i,t} + \lambda_i + \lambda_t + \varepsilon^2_{i,t} \quad (3)$$

$$Loan_{i,t} = \gamma_0 + \gamma_1 Digital_{i,t} + \gamma_2 Z-Score_{i,t} + \sum \gamma_m Con_{i,t} + \lambda_i + \lambda_t + \varepsilon^3_{i,t} \quad (4)$$

β_0 and γ_0 are the constant terms; $\beta_1 \sim \beta_m$, $\gamma_1 \sim \gamma_m$ are the regression coefficients; m=2, 3...7 in Eq. (3), m=3, 4...8 in Eq. (4); $\varepsilon^2_{i,t}$, $\varepsilon^3_{i,t}$ are the random error terms of Eqs. (3) and (4), respectively; and is the random error term of Eq. (3) and (4).

Based on equations (3) and (4), the results of the mediation effect test are shown in Table 2.Column (3) shows the regression results of the digital transformation of commercial banks on risk-taking, and the regression coefficient of the digital transformation of commercial banks is significantly negative at the 5% level. The regression results of adding the mediator variable risk taking are shown in Column (4). The results show that the regression coefficient of digital transformation on the level of credit supply is significantly positive, while the regression coefficient of risk taking on the level of credit supply is significantly negative, and the absolute value of the regression coefficient of digital transformation of commercial banks is smaller than the benchmark regression results, which indicates that with the deepening of the digital transformation of commercial banks, the risk taking of the banks has been suppressed, which is conducive to the increase of the level of credit supply of commercial banks, and the hypothesis H2 has been verified.

4.1.3 Moderating effects test

In order to analyse whether there is a moderating effect of digital inclusive finance in the process of commercial banks' digital transformation affecting credit supply, this paper constructs a moderating effect model as follows:

$$Loan_{i,t} = \eta_0 + \eta_1 Digital_{i,t} + \eta_2 DFI_{i,j,t} + \eta_3 Digital \times DFI_{i,j,t} + \sum \eta_m Con_{i,t} + \lambda_i + \lambda_t + \varepsilon^4_{i,t} \quad (4)$$

where j denotes the province; η_0 is the constant term of equation (4); and $\eta_1 \sim \eta_m$ is the regression coefficient, where m=4, 5...9; $Digital \times DFI$ is the interaction term between digital transformation and digital financial inclusion; $\varepsilon^4_{i,t}$ is the random error term of equation (4).

Based on equation (4), the corresponding regression results of the moderating effect of digital inclusive finance are shown in column (5) of Table 2, and the regression coefficient of $Digital \times DFI$ is -0.0093, which is significant at the 1% level, and the sign of the coefficient of the digital transformation of commercial banks on the credit supply is opposite to the sign of the coefficient of the digital transformation of commercial banks on the supply of credit, indicating that the development of digital inclusive finance will weaken the impact of the weak digital transformation of commercial banks on the level of the supply of credit, and the assumption of H3 has been verified.

Table 2 Direct, mediated and moderated effects regression results

variant	(1) Loan	(2) Loan	(3) Z-Score	(4) Loan	(5) Loan
Digital	0.0114 *** (2.94)	0.0156 *** (4.11)	-0.0019** (-2.10)	0.015 *** (3.94)	0.0501*** (6.78)
Z-Score				-0.358** (-2.54)	
DFI					-0.0629** (-1.99)
Digital×DFI					-0.0093 *** (-2.72)
Controls		control	control	control	control
Bank/Year	control	control	control	control	control
N	1043	1043	1043	1043	1043
R2	0.800	0.815	0.431	0.817	0.821

4.2 Robustness Tests

4.2.1 Replacement of explanatory variables

In this paper, we use bank loan size (Loan2) as a proxy variable for bank credit supply, which is calculated as the natural logarithm of the bank's end-of-period loan balance, to re-examine the impact of commercial banks' digital transformation on bank credit supply. The regression results, as shown in column (1) of Table 3, show that the coefficient of digital transformation of commercial banks is still significantly positive at 1% level, which is consistent with the findings of the previous study.

4.2.2 Exclusion of special samples

Considering the possible impact of the new crown epidemic on the use of digital technology and the supply of commercial bank credit, this paper re-examines the impact of digital transformation on bank credit supply after excluding the 2020-2022 sample. The regression results are shown in column (2) of Table 3, and the significance of the regression coefficients for digital transformation has not changed compared to the results in column (2) of Table 2, consistent with the results of the direct effect test.

Table 3 Robustness test

variant	(1)	(2)
	Loan2	Loan
Digital	0.0473***	0.0115***
	(4.04)	(2.68)
Controls	control	control
Bank/Year	control	control
N	1043	728
R2	0.994	0.824

5 Conclusions and Management Insights

The main conclusions of this paper are as follows:(1) digital transformation of commercial banks enhances the level of banks' credit supply, in line with Hughes et al.[1] 's technology-enabling view; (2) risk-taking plays a mediating role in digital transformation to enhance the level of commercial banks' credit supply, revealing that digital transformation optimises resource allocation by suppressing risk appetite, distinguishing from Fuster et al.[3] 's algorithmic risk accumulation conclusion. (3) Digital financial inclusion negatively moderates the role of commercial banks' digital transformation on credit supply, suggesting that external competition diversion effect compresses banks' exclusive returns, consistent with the theory of Han et al.[13] .

Based on this, three levels of insights are proposed: theoretical level: revealing the dynamic balance mechanism of "technological empowerment-risk inhibition-competitive constraints", which makes up for the inadequacy of the single-path explanation; managerial level: commercial banks need to establish an intelligent risk control system and dynamic threshold monitoring, with a focus on optimising algorithmic ethical review and risk buffer mechanism; policy level: Regulators should promote the construction of regional data sharing platforms and implement adapted differentiated governance. Research limitations of this paper: the sample is limited to the Chinese banking industry, the dynamic lag effect of digital transformation needs to be tracked in the long term, and the synergistic mechanism analysis of cross-institutional competition of fintech companies is not included.

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Research on Corporate Social Responsibility Synergy in Food Supply Chain: Insights from Nestlé Company

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Abstract: This study employs a case study methodology to analyze a sample of major food supply chain companies from 2022 to 2024, with Nestlé as a primary focus. It proposes actionable recommendations to enhance the synergistic effects of corporate social responsibility (CSR) in food supply chains. Grounded in stakeholder theory, the paper dissects the content system of CSR, identifies three critical factors (resources, synergy, and systems), and proposes a three-dimensional synergistic promotion mechanism integrating supply chain governance, government regulation, and social supervision. This framework aims to advance supply chain sustainability, foster CSR compliance, and elevate social responsibility standards. In an era of stringent regulations, heightened environmental awareness, and escalating ESG demands, collaborative governance is pivotal for sustainable food industry development.

Keywords. Food supply chain; corporate social responsibility; synergistic promotion mechanism

1. Introduction

In recent years, frequent food safety issues have highlighted the lack of corporate social responsibility (CSR) in the food supply chain. Against the backdrop of tightening global regulation, increasing consumer environmental awareness, and rising investor ESG requirements, there is an urgent need for companies to profoundly change their supply chain models to achieve synergistic enhancement of economic, environmental, and social values. The purpose of this paper is to explore the synergistic governance mechanism of CSR in the food supply chain, to enhance the level of social responsibility and economic benefits of the supply chain, and to promote the sustainable development of the food industry. At present, the research on CSR has achieved many results, but the research on CSR synergy in food supply chain is still in the primary stage and lacks a systematic theoretical framework. Under the wave of the Internet, some unscrupulous food manufacturers have utilized e-commerce platforms to substitute the best for the worst, which undermines the efficiency of the entire supply chain. Therefore, it is particularly necessary to conduct collaborative research to promote the fulfillment of CSR.

In the current context, the environment for food enterprises to fulfill their social responsibility has changed significantly, and the issue of supply chain social

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responsibility has received widespread attention. Based on stakeholder theory, food supply chain companies should comprehensively consider all types of stakeholders in their ecosystems and environments to enhance social responsibility in multiple ways[1]. Using the business ecosystem theory, food supply chain enterprises can comprehensively analyze their ecosystems and environments to enhance their social responsibility in a variety of ways. Enterprises should take the initiative to assume social responsibility, prioritize the life safety and health of consumers, and ensure the healthy development of the food industry. This will also help stakeholders to understand the fulfillment of CSR more comprehensively and promote the expansion of its systemic connotation and sustainable development. A notable example is Nestlé. Nestlé has been a leader in social responsibility in the food industry. The company has established a comprehensive and rigorous supplier management system and regularly audits its suppliers to ensure that they comply with high social and environmental standards. Through these efforts, Nestlé not only enhances its own socially responsible image, but also drives positive change throughout the food supply chain ecosystem.

2.Current status of research at home and abroad

2.1 Current status of foreign research

Foreign scholars' research on CSR is more mature, mainly focusing on the following aspects: Ciliberti[2] explored the impact of purchasing social responsibility on supply chain relationship and supplier performance, and the study showed that the former has a direct positive impact on the latter, and an indirect impact on supplier performance through improved trust and co-operation. Walker and Jones[3] conducted a study on the coordination of supply chain networks under CSR, and the results show that supply chain networks that consider CSR are more profitable than those that do not, even without coordination. Hutchins[4] studied the principal-agent and normative issues of CSR in supply chains, and argued that CSR norms can effectively solve the problem of supply chain SMEs have no incentive to fulfil CSR. Fallah[5] et al. show that CSR is mitigating the risk of global supply chain by building a CSR model for global supply chain. In addition, global studies on CSR also point out that CSR practices vary across countries and regions, which are closely related to local laws and regulations, cultural contexts and market environments.

2.2 Current status of domestic research

Domestic scholars have also achieved some results in the study of CSR in food supply chain: Jiang Qijun[6] proposed five strategies for CSR management in food supply chain from the perspective of food supply chain mainly through the characterisation of CSR in food enterprises. Li Nianqin[7] divides social responsibility into three levels, i.e., economic and legal responsibility, ethical responsibility and voluntary responsibility, which lays the foundation for food supply chain enterprises to fulfil their CSR. Zhao Yaling[8] analysed and researched the problems and governance of food CSR from the perspective of global supply chain, based on which governance countermeasures were proposed. In addition, domestic studies also point out that the fulfilment of CSR in the food supply chain is of great significance in enhancing corporate reputation, strengthening consumer trust and promoting sustainable corporate development. However, the current status of financial reports disclosed by most food enterprises in China shows that their information disclosure is to a large extent difficult to adequately reflect the current status of their social responsibility fulfilment, and more research and development is needed.

3. Influencing Factors of Collaborative Promotion of Corporate Social Responsibility in the Food Supply Chain

3.1 Resource factors

The fulfilment of corporate social responsibility necessitates the investment of multiple resources, and these resource factors are important aspects that influence the synergistic promotion of corporate social responsibility in the food supply chain. Specifically, they include the commitment of top management, the awareness and attitude of employees, enterprise culture, development planning, strategic alliance, management strategy, reputation, and learning and innovation ability. For example, the commitment of top management can provide strategic direction and resource support for the promotion of CSR, while the awareness and attitude of employees directly affect the effectiveness of CSR implementation[9] . In addition, the financing ability and profitability level of an enterprise determines whether it has enough funds to invest in its social responsibility programme, while the size and culture of the enterprise affects the scope and depth of its social responsibility implementation. At the same time, a good coordination system and development plan can help enterprises integrate resources more effectively to achieve their social responsibility goals. Strategic alliances and management strategies can help companies build co-operative relationships with external stakeholders to jointly promote social responsibility. An enterprise's reputation and ability to learn and innovate, on the other hand, can help enhance its competitiveness and influence in the field of social responsibility[10].

3.2 Synergies

Synergy theory suggests that node enterprises in the food supply chain should consciously fulfil their CSR, and that synergistic factors have a direct impact on the synergistic promotion of CSR in the food supply chain[11]. These synergistic factors mainly include benefit distribution mechanism, decision-making coordination mechanism, information sharing mechanism, risk control mechanism and so on. The benefit distribution mechanism ensures that the inputs of enterprises in the supply chain nodes in the social responsibility programme can be reasonably rewarded, thus increasing the enthusiasm of enterprises to participate. Decision-making coordination mechanism can help enterprises reach consensus in the decision-making process of social responsibility and avoid the difficulties caused by divergent opinions. The information sharing mechanism can promote communication among supply chain enterprises and ensure the transparency and timely transmission of social responsibility information. Risk control mechanism can help enterprises identify and respond to possible risks in the process of social responsibility promotion to ensure the smooth implementation of the project. Through the effective operation of these synergistic factors, food supply chain enterprises can better achieve their social responsibility goals and enhance the social responsibility level of the whole supply chain[12].

3.3 Institutional factors

Institutional theory suggests that the fulfilment of CSR by enterprises is influenced by institutional factors of internal resources and external environment. Institutional factors affecting the synergistic promotion of CSR in the food supply chain mainly include regulatory institutional factors, normative institutional factors and cognitive institutional factors. Regulatory institutional factors involve government laws, regulations and policy requirements, which prompt enterprises to fulfill certain social responsibilities, such as environmental protection and labour rights protection. Normative institutional factors include industry standards, internal rules and regulations, etc., which can guide enterprises to fulfil their social responsibilities in accordance with established standards and processes. Cognitive institutional factors involve society's perceptions and expectations of CSR. The concerns and demands of stakeholders such as consumers, the media, and non-governmental organisations (NGOs) on CSR will influence the CSR behaviour of enterprises. For example, consumers' high concern for food safety will prompt food companies to strengthen quality control and traceability systems. At the same time, the supervisory role of NGOs and the media should not be ignored, as they can prompt enterprises to better fulfil their social responsibility through public opinion pressure. Through the combined effect of these institutional factors, food supply chain enterprises can better promote collaborative governance of social responsibility and achieve sustainable economic, social and environmental development[13].

4. Construction of a three-dimensional synergistic promotion mechanism

4.1 Food supply chain governance mechanisms

The food supply chain governance mechanism is the basis for achieving collaborative promotion of CSR, and includes two parts: the supply chain synergy mechanism and the internal corporate governance mechanism. The purpose of the supply chain synergy mechanism is to realise the collaborative governance of CSR at the supply chain level, which mainly includes the benefit distribution mechanism, information sharing mechanism, product traceability mechanism, risk control mechanism and product recall mechanism. The benefit distribution mechanism ensures that the inputs made by enterprises at each node of the supply chain in the social responsibility programme can be reasonably rewarded, thus increasing the enthusiasm of enterprises to participate. The information sharing mechanism can promote communication and cooperation among supply chain enterprises and ensure the transparency and timely transmission of social responsibility information. The product traceability mechanism enhances consumer trust in food safety by establishing a full traceability system from raw materials to final products. Risk control mechanism helps enterprises identify and respond to risks that may arise in the process of promoting social responsibility and ensures the smooth implementation of the project. The product recall mechanism enables timely recall of products in case of problems and reduces the impact on consumers and society[14].

The purpose of the internal corporate governance mechanism is to comprehensively strengthen the internal governance of CSR in the food supply chain, mainly through the establishment of a corporate ethics organisation, the strengthening of corporate culture construction, and the regular publication of CSR reports. The establishment of a corporate ethics organisation can provide strategic direction and resource support for the promotion of CSR, while the construction of corporate culture helps to enhance employees' awareness and participation in CSR. Publishing CSR reports on a regular basis not only enhances the transparency of enterprises, but also accepts social supervision and improves the social image of enterprises.

4.2 Government-led regulatory mechanisms

The government-led regulatory mechanism is an important external pressure to promote the concerted promotion of CSR in the food supply chain, which mainly includes the formulation of incentive policies, the strengthening of training for entrepreneurs, the improvement of laws and regulations, and the streamlining of regulatory institutions. The government encourages enterprises to actively fulfil their social responsibility by formulating incentive policies, such as tax concessions and financial subsidies. Strengthen training for entrepreneurs to enhance their knowledge of CSR and their management ability. Formulate and improve laws and regulations to clarify the responsibilities and obligations of enterprises in the areas of food safety and environmental protection, so as to provide a legal basis for the fulfilment of their social responsibilities. Streamlining regulatory systems and mechanisms, strengthening coordination between agricultural and rural departments and market regulators, and ensuring seamless regulation at all stages of the food supply chain.

4.3 Social monitoring mechanisms

The social supervision mechanism is an important guarantee for the concerted promotion of CSR in the food supply chain, including the guiding and regulating role of NGOs such as industry associations, the public opinion supervision mechanism, consumer awareness of CSR and the establishment of a social participation mechanism for CSR management. NGOs such as industry associations guide enterprises in fulfilling their social responsibility by formulating industry standards and norms, and at the same time assessing and supervising the social responsibility status of enterprises. The public opinion monitoring mechanism prompts enterprises to pay more attention to the fulfilment of social responsibility and enhances social transparency through media reports and supervision. Consumers' awareness and demand for CSR can influence enterprises through the market mechanism, prompting enterprises to fulfil their social responsibility more actively. The establishment of a social participation mechanism for CSR management encourages the active participation of all sectors of society, creating a favourable atmosphere for collaborative supervision.

Supply chain governance, government regulation and social supervision are interdependent and interact with each other to promote the collaborative governance of CSR in the food supply chain. The supply chain governance mechanism provides internal motivation and a synergistic framework for enterprises, the government regulation mechanism provides external pressure through policy guidance and legal constraints, and the social supervision mechanism enhances enterprises' self-awareness of CSR through public participation and public opinion supervision. In practice, the synergistic effect of the three can effectively enhance the level of CSR in the supply chain and realize the sustainable development of economy, society and environment.

5 Case studies

As a globally renowned food manufacturer, Nestlé has always been committed to promoting corporate social responsibility and sustainable development. Through a series of innovative initiatives and strategic planning, Nestlé has not only set industry benchmarks in food safety and supply chain management, but also achieved remarkable results in the fulfilment of social responsibility.

5.1 Sustainable supply chain management

Nestlé has established stringent food safety standards globally and employs advanced information technology in its supply chain management to ensure food safety from the farmland to the consumer's table. Nestlé promotes sustainable sourcing through long-term partnerships with suppliers to ensure the quality and sustainability of raw materials. For example, Nestlé's Global Dairy Development Programme improves farm sustainability and milk quality by working with milk producers. In addition, Nestlé helps suppliers to improve production efficiency and environmental protection through technical training and resource support.

5.2 Corporate social responsibility fulfilment

Nestlé has adopted a multi-dimensional strategy for social responsibility fulfilment. Firstly, Nestlé is committed to enhancing the nutritional value of its products, and assesses its products through the Health Star Rating system to ensure that they meet nutritional requirements. Secondly, Nestlé promotes environmental protection and sustainable development globally, and actively combats climate change through the use of renewable energy and the reduction of greenhouse gas emissions. For example, Nestlé is committed to achieving 100 per cent renewable electricity use by 2025. In addition, Nestlé helps to improve the quality of life in communities through community development projects such as the Nestlé Healthy Kids programme and the Dairy Farming Training Centre.

5.3 Creating shared value

Nestlé's philosophy of "Creating Shared Value" (CSV) is at the centre of its social responsibility strategy. Nestlé believes that the success of a company depends not only on financial gain, but also on creating a positive impact on society. Through the CSV concept, Nestlé is closely aligned with the needs of society in three areas: nutrition, water and rural development, to promote sustainable development. For example, Nestlé's promotion of the coffee plantation industry in Yunnan not only helps local farmers to increase their income, but also contributes to the sustainable development of the community.

Through these initiatives, Nestlé has not only enhanced its own brand image and market competitiveness, but also set an example of social responsibility for the entire food industry. Nestlé's practice shows that by actively fulfilling its social responsibility, an enterprise can not only enhance its own sustainable development capability, but also bring positive impacts to the society and the environment.

6. Conclusions and outlook

6.1 Conclusion

The collaborative promotion of corporate social responsibility in the food supply chain is a complex systematic project, which is influenced by many factors. This paper constructs the content system of CSR in food supply chain from the perspective of stakeholders, analyzes the key factors affecting the synergistic promotion, and proposes a three-dimensional synergistic promotion mechanism covering supply chain governance, government regulation and social supervision. The study shows that through the synergy of these three mechanisms, it can effectively promote the collaborative governance of CSR in the food supply chain and enhance the level of social responsibility and sustainable development of the whole supply chain. Nestlé's successful practice shows that active fulfillment of social responsibility not only enhances the sustainable development ability of enterprises, but also brings positive impacts to society and the environment. The collaborative governance of CSR in the food supply chain is particularly important in the context of tightening global regulation, increasing consumer awareness of environmental protection, and rising investor ESG requirements. Based on the findings, this paper makes relevant recommendations, including improving transparency of supply chain operations, increasing investment in sustainable sourcing, and enhancing stakeholder engagement. These recommendations emphasize the importance of stakeholder collaboration and transparency in effective CSR governance, and also provide ideas for resolving potential conflicts between short-term profitability and long-term sustainability goals.

6.2 Outlook

Future research can further explore the characteristics, connotations and management modes of CSR in food supply chains of different industries, so as to enrich and improve the theory of food supply chain management. At the same time, taking into account the characteristics of the food industry, we can try to construct a social responsibility system applicable to the food industry and explore the evaluation model applicable to the constructed system. In addition, with the development of digital technology, further research can be conducted in the future on how to use big data, blockchain and other technologies to improve the transparency and traceability of the food supply chain, so as to better promote the fulfilment of corporate social responsibility. Through these studies, more comprehensive and effective guidance can be provided to enterprises and society to promote the sustainable development of the food industry.

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A Study on the Impact of Dynamic Capabilities on the Intelligent Transformation of Advanced Manufacturing

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Abstract. Taking the data of A-share listed companies in Shanghai and Shenzhen from 2015 to 2023 as a sample, this data was analyzed using empirical methods, fixed-effects, and explicit regression analysis. The findings indicate that dynamic capabilities and the threefold dynamic capabilities promote the intelligent transformation of advanced manufacturing. The findings of this study provide a framework for enterprises to navigate the process of intelligent transformation, address the research gap regarding the role of dynamic capabilities in this field, and demonstrate the differentiated effects of various dimensions of dynamic capabilities, which can inform both managerial practices and industrial policy.

Keywords. Intelligent transformation, dynamic capabilities, advanced manufacturi-ng

1. Introduction

Manufacturing remains vital to national economies, with advanced manufacturing reshaping technologies, production, and strategies to meet future demands from rising affluence and population growth. Technological innovation is essential for emerging economies like China as traditional demographic and resource advantages wane. Focusing on knowledge- and technology-intensive sectors can uncover new comparative advantages and enhance global competitiveness. The "Made in China 2025" strategy integrates digital technologies into critical manufacturing processes, driving industrial upgrading and global value chain ascension[1].

Amid rapid digital advancements—AI, big data, cloud computing, IoT—enterprises must adapt quickly. Teece[2] proposes the concept of dynamic capabilities, the core of which includes sensing, seizing and reconfiguring capabilities. These capabilities assist organisations in identifying opportunities and challenges and making subsequent strategic adjustments during intelligent transformation. Teece's Dynamic Capability Theory addresses the shortcomings of the resource-based view[3], which, due to its static perspective, cannot fully explain the differences in competitive advantage between firms

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in dynamic environments. Over the past two decades, research in this area has moved from conceptual clarification to multidimensional, cross-level analysis, achieving significant theoretical depth and research breadth. Dynamic capabilities, characterized by an organization's capacity for integration, develop, and reconfigure resources, are key to sustaining competitiveness and enabling intelligent transformation[4]. However, prior research often reduces these capabilities to a single dimension[5] (e.g., absorptive capacity), and most studies focus on the mediating mechanisms[6] of dynamic capabilities. Therefore, this study focuses on exploring the direct effect mechanisms of dynamic capabilities and the influence paths of each sub-capability.

Dynamic capability theory is a crucial perspective for analyzing the digital transformation of enterprises. Many scholars have studied the relationship between dynamic capabilities and digital transformation, laying a solid theoretical foundation in this field. Warner et al.[7] argue that digital transformation is a continuous process for mature companies, driven by agility to change business models, collaboration methods, and ultimately corporate culture. Leso B H et al.[8] proposed a dynamic capability framework in five action areas to help organizations achieve digital maturity and continuous change. Previous research provides an important theoretical reference for further exploring the deep connection between dynamic capability and digital transformation.

This study explores how dynamic capabilities directly affect the intelligent transformation of advanced manufacturing by constructing a "perception-reconstruction-learning" framework. Through text mining of the data of A-share listed manufacturing companies in Shanghai and Shenzhen from 2015 to 2023, the contributions of this study include: (1) establishing a comprehensive framework that transcends the perspective of isolated capabilities; (2) Divide dynamic capabilities into three categories: learning, integration and coordination, and refactoring, and evaluate their impact; (3) Extending the theory of dynamic capability to the field of smart manufacturing provides empirical insight into the transformation path.

2. Theoretical analysis and research hypothesis

2.1. Dynamic Capabilities and Intelligent Transformation

The digital economy and AI have driven a research shift toward intelligent transformation, where software and robotics increasingly replace human decision-making. This shift enhances design, production, and marketing through automation, improving total factor productivity via transparency, real-time scheduling, and efficient resource use[9]. It also advances green innovation and reduces emissions[10]. Despite growing research, many manufacturing firms struggle to adapt to rapid technological changes and market volatility.

Dynamic Capability Theory[2] provides a lens to understand how firms sustain competitiveness by reconfiguring resources in changing environments, moving beyond the static resource-based view[3]. The theory has evolved to emphasize coordination, integration, and learning capabilities across organizational levels[11]. These capabilities are crucial for digital transformation, supporting the alignment of digital tools with internal processes and structures[12].

This study investigates how dynamic capabilities—specifically perceptual, integrative, and reconfiguration skills—drive intelligent transformation in advanced

manufacturing. It focuses on firms' ability to recognize technological trends, meet customer demands through data analysis, and restructure for agility[13], forming the basis for Hypothesis 1.
Hypotheses 1: Dynamic capabilities has a positive effect on the intelligent transformation of advanced manufacturing.

2.2. The threefold Dynamic Capabilities and Intelligent Transformation

According to dynamic capabilities theory[11], coordination and integration capabilities are foundational for cross-functional resource optimization, technology interoperability, and knowledge flow redesign. Rooted in the "Seizing" capability[14], these abilities foster collaboration and innovation by aligning internal and external resources[15] , thereby facilitating agile, technology-ready processes essential for intelligent transformation.

Reconfiguration capability, another core dimension, enables firms to adapt to market shifts by reorganizing operational structures[11]. Through continuous adjustment and learning[16], firms can reallocate resources and restructure departments—such as integrating R&D and IT—to support intelligent technology implementation and strategic responsiveness[17].

Learning capability, drawn from absorptive capacity theory[18] and dynamic capability theory[11], emphasizes acquiring and transforming external knowledge. It supports ongoing adaptation to technological change and accelerates internal innovation by reducing search costs and enhancing tacit knowledge transfer[19], helping firms overcome transformation bottlenecks[20].

Based on the above, the following Hypothesis 1 is proposed:
Hypotheses 2a: Coordination and integration capabilities has a positive effect on the intelligent transformation of advanced manufacturing.
Hypotheses 2b: Reconfiguration capabilities has a positive effect on the intelligent transformation of advanced manufacturing.
Hypotheses 2c: Learning abilities has a positive effect on the intelligent transformation of advanced manufacturing.

3. Research design

3.1. Data sources and sample selection

This study selects A-share listed advanced manufacturing companies in Shanghai and Shenzhen that meet the 2012 CSRC Industry Classification from 2015 to 2023, with data from CSMAR, WIND databases and Juchao Information Network. To reduce the effect of outliers, all variables were Windsorized at the 1% level. The excluded sample includes: companies that do not belong to the manufacturing sector, ST and delisted companies, and companies with missing data. The final dataset contains 741 firms and 6,669 firm-year observations.

3.2. Measurement of variables

3.2.1. Dependent variable: Intelligent Transformation (IT)

This research adheres to the methodology[21], using text analysis to assess intelligent transformation based on 27 intelligence-related keywords[22]. The MD&A section of annual reports, where senior management outlines strategic directions, is the primary data source. The analysis involves: (1) manually collecting annual reports, (2) extracting the MD&A sections, and (3) segmenting the text using the Python "jieba" module. The extent of intelligent transformation is quantified by the ratio of a firm's keyword frequency in a specific year to the aggregate frequency of those terms across all firms within the same industry and year. The specific formula is as follows:

$$IT_{i,t} = q_{i,t} \Big/ \sum_{t}^{i} q_{i,t} \tag{1}$$

In this study, $q_{i,t}$ denotes the number of keywords in a company's annual report, where i is the company code and t is the year. A higher $IT_{i,t}$ value indicates a deeper level of intelligent transformation.

Table 1. List of Intelligent Transformation keywords

Categorization	Keywords
Intelligent Transformation(IT)	Intelligent Manufacturing, Digitalization, Intelligentization, Informatization, Automation, Cloud Computing, Cloud Platform, Internet of Things (IoT), Data Visualization, Cyber-Physical System (CPS), Networked Physical System, Big Data, Sensing Technology, Cloud Manufacturing, Active Manufacturing, Smart Manufacturing, Intelligent Enterprise, Smart Terminal, Intelligent Recognition, Robot, Industry 4.0, Industrial Internet, Internet Plus, Human-Machine Interaction, Sensor, Controller, Data Mining

3.2.2. Explanatory variable: Dynamic Capabilities(DCs)

In this paper, the dynamic capabilities of enterprises are evaluated through three sub-dimensions: coordination and integration, organizational restructuring, and learning and absorption, and the CRITIC weighting method is used to quantify them[6][23]. Coordination and integration capability (CRI) is measured by the ratio of R&D investment, refactoring capability is evaluated by return on assets (ROA), and learning ability is quantified by the proportion of employees' educational qualifications[6]. The CRITIC method determines the weights of these indicators as follows:

$$DC_S = 0.09292393 \times CRI + 0.20257953 \times REC + 0.70449655 LEN \tag{2}$$

3.2.3. Control variables.

As referenced in the relevant literature[21], the following variables are selected for analysis: gearing ratio (LEV), first most significant shareholder shareholding (Top1), management shareholding (Mshare), management expense ratio (Mfee), average monthly excess turnover (Dturn), and nature of equity (SOE). The variable definitions and descriptions are detailed in the following table.

3.3. Modeling

Based on the above theoretical analysis, to investigate the direct influence of dynamic capabilities and three-dimensional sub-capabilities on the intelligent transformation of advanced manufacturing, this paper constructs the following benchmark model:

$$IT_{i,t}=\alpha_0+\alpha_1 DCs_{i,t-1}+\beta Control_{i,k,t}+\delta_i+\gamma_i+\theta_i+\varepsilon_{i,t} \tag{3}$$

$$IT_{i,t}=\alpha_0+\alpha_1 CRI_{i,t-1}+\beta Control_{i,k,t}+\delta_i+\gamma_i+\theta_i+\varepsilon_{i,t} \tag{4}$$

$$IT_{i,t}=\alpha_0+\alpha_1 REC_{i,t-1}+\beta Control_{i,k,t}+\delta_i+\gamma_i+\theta_i+\varepsilon_{i,t} \tag{5}$$

$$IT_{i,t}=\alpha_0+\alpha_1 LEN_{i,t-1}+\beta Control_{i,k,t}+\delta_i+\gamma_i+\theta_i+\varepsilon_{i,t} \tag{6}$$

Considering a time lag between a firm's improvement in dynamic capabilities and three-dimensional sub-capabilities and its impact on intelligent transformation, previous studies have adopted a one-period lag for the explanatory variables. This study similarly applies a one-period lag to all control variables in the model. Where: i, t, k represent firm, time, and province, respectively; $DCs_{i,t-1}$ represents the lagged dynamic capability of the firm; $IT_{i,t-1}$represents the lagged level of intelligent transformation of the firm; $CRI_{i,t-1}$ represents the lagged coordination and integration capability of the firm; $REC_{i,t-1}$ represents the lagged restructuring capability of the firm; $LEN_{i,t-1}$ represents the learning capacity of the lagging period. $Control_{i,t}$ represents the control variable, δ_i represents the individual fixed effect, $\gamma_i$represents the time fixed effect, θ_i represents the provincial fixed effect, and $\varepsilon_{i,t}$ is the error term.

4. Empirical analysis

4.1. Descriptive analysis and matrix of correlation coefficients

The table shows that the average value of intelligent transformation is 0.004, indicating that the sample companies have a low level of intelligent transformation. The mean value of the dynamic capabilities (DCs) was 0.338 and the standard deviation was 0.157, indicating that the dynamic capabilities of the sample companies differed less. The results show that there is a significant statistical relationship between dynamic capabilities (DCs) and intelligent transformation (IT), indicating that the improvement of dynamic capabilities is related to the improvement of intelligent transformation.

Table 2. Results of descriptive statistics

Variable	Obs	Mean	Std.Dev	Min	Max
Intelligent	6669	0.004	0.006	0	0.036
DCs 2	6607	0.338	0.157	0.149	0.795
CCS	6102	0.094	0.079	0.008	0.413
CRI RD	6830	6.946	5.534	0.7	33.56
REC TTM	6888	0.051	0.075	-0.251	0.252
Len	6649	0.287	0.221	0.022	0.926
Lev	6640	0.386	0.183	0.054	0.824
ROE	6630	0.062	0.121	-0.532	0.327
Top1	6640	0.306	0.137	0.079	0.675
Dturn	5915	-0.164	0.584	-2.457	1.297
Mshare	6502	0.191	0.208	0	0.7
Mfee	6640	0.079	0.057	0.011	0.335
SOE	6637	0.186	0.389	0	1

Table 3 shows the correlation coefficient matrix between major variables. There is a significant positive correlation between Intelligent Transformation (IT) and Dynamic Capabilities (DCs). The sub-dimensions of Dynamic Capabilities (Coordination and Integration Capability CRI, Restructuring Capability REC) are significantly correlated with Intelligent Transformation at the 5% level, while Learning Capability (LEN) is significantly correlated with Intelligent Transformation at the 1% level. This indicates that the higher the level of Intelligent Transformation, the stronger each sub-dimension of Dynamic Capabilities.

4.2. Main effects tests

The coefficient of 0.0108 for dynamic capability in column (1) of Table 4, compared to 0.0112 for dynamic capability with control variables in column (2), indicates a significant positive correlation, thereby supporting the primary effect of dynamic capability positively affecting intelligent transformation and validating Hypothesis 1.

Table 3. Matrix of correlation coefficients

	IT	DCs	CRI	REC	Len
IT	1.000				
DCs	0.117***	1.000			
	(0.000)				
CRI	0.025**	0.592***	1.000		
	(0.040)	(0.000)			
REC	0.010**	-0.006	-0.195***	1.000	
	(0.020)	(0.644)	(0.000)		
LEN	0.117***	0.999***	0.592***	-0.048***	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	

Table 4. Main effects test

Variable	**(1)** **IT**	**(2)** **IT**
DCs	0.0108***	0.0112***
	(15.55)	(14.93)
Constant	0.000451*	0.000254
	(1.86)	(0.70)
Control	–	YES
Year	YES	YES
Industry	YES	YES
Province	YES	YES
N	5314	5091
R2	0.229	0.232

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Columns (1)-(3) of Table 5 add the three sub-capabilities as core explanatory variables, and the regression results show that the three sub-capabilities significantly positively impact intelligent transformation. The coefficients in columns (4)-(6) are positive and significant after adding the control variables, consistent with the previous results. This indicates that each three-dimensional sub-competency of dynamic capabilities promotes intelligent transformation, which verifies hypotheses 2a, 2b, and 2c.

Table 5. The threefold Dynamic Capabilities effects test

Variable	**(1)** **IT**	**(2)** **IT**	**(3)** **IT**	**(4)** **IT**	**(5)** **IT**	**(6)** **IT**
CRI	0.000137***	–	–	0.000153***	–	–
	(9.92)			(9.51)		
REC	–	0.00234**	–	–	0.00302**	–

		(2.56)			(2.49)	
LEN	–	–	0.00532***	–	–	0.00547***
			(15.55)			(14.91)
Constant	0.00275***	0.00354***	0.00219***	0.00227***	0.00227***	0.00131***
	(24.12)	(42.54)	(18.78)	(6.50)	(6.50)	(3.82)
Control	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES	YES
Province	YES	YES	YES	YES	YES	YES
N	5488	5520	5337	5201	5201	5114
R2	0.202	0.191	0.231	0.198	0.198	32.78

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

4.3. Robustness tests

This study performs robustness assessments employing three methodologies.: (1) Replacing the explanatory variable measurement method by standardizing the three sub-capabilities, following the method[6]; (2) Limiting the sample period to before 2020 to avoid the effects of the COVID-19 outbreak; and (3) Adding city-level fixed effects to control for unobservable factors like economic development and policy environment. As shown in Table 6, the robustness test results align closely with the benchmark regressions, reinforcing the validity and reliability of the study's conclusions.

Table 6. Robustness test

Variable	**(1)** **IT**	**(2)** **IT**	**(3)** **IT**
DCs	–	0.00859***	0.00706***
		(10.09)	(13.02)
DCs_2	0.0152***	–	–
	(14.77)		
Control	YES	YES	YES
Year	YES	YES	YES
Industry	YES	YES	YES
Province	YES	YES	YES
City	–	–	YES
N	5201	2597	5082
R2	0.230	0.256	0.316

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

5. Conclusion and exploration

This study explores the driving mechanisms of dynamic capabilities in the intelligent transformation of advanced manufacturing, leading to the following conclusions: (1) By integrating dynamic capability theory with research on intelligent transformation, a causal chain for intelligent transformation has been established; (2) It demonstrates that coordination and integration capabilities, restructuring capabilities, and learning capabilities play a crucial role in promoting intelligent transformation. These findings are consistent with those of Warner et al.[7] and Leso B H et al.[8], expanding the theory of dynamic capabilities and providing micro-level evidence for companies to overcome traditional manufacturing constraints.

The framework provides actionable insights for companies to restructure internal resources and absorb external knowledge to break path dependence. To achieve this, companies should: 1) institutionalize learning systems; 2) invest in skill enhancement; 3) promote open innovation. Beyond the Chinese context, these conclusions have broad implications for global manufacturing. As the pressure of digitalization and technological advancement intensifies, the ability of companies to restructure and absorb external knowledge becomes crucial for survival and development.

In terms of methodology, this study measures the level of intelligent transformation through text mining. Although effective, it is subject to subjectivity and limitations in data availability. In the future, combining human annotation or deep learning techniques can enhance the accuracy of the assessment. Additionally, future research could introduce questionnaires to delve into the subjective pathways of dynamic capability formation and further explore the five dimensions of dynamic capability.

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Research on the Influence Mechanism of the "Four Chains" Integration of Digital Technology-Enabled Manufacturing Industry

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Abstract: On the basis of constructing a theoretical framework of "four-chain" integration of manufacturing industry empowered by digital technology, the direct and indirect influence mechanisms of digital technology on "four-chain" integration of manufacturing industry are empirically examined by selecting provincial panel data from 2012 to 2022, and the role mechanisms of government and market are further explored. Based on the provincial panel data from 2012 to 2022, we empirically examined the direct and indirect influence mechanisms of digital technology on the integration of the four chains of manufacturing industry, and further explored the role of the government and the market. It is found that digital technology has a significant role in promoting the integration of the four chains of manufacturing industry; the mechanism test finds that digital technology not only directly improves the degree of integration of the four chains of manufacturing industry, but also realizes the integration of the four chains of manufacturing industry through the intermediary path of financial development, which is the most effective way to promote the integration of the four chains of manufacturing industry. The mechanism test finds that digital technology not only directly enhances the degree of integration of the "four chains" of manufacturing industry, but also realizes the systematic empowerment of the integration of the "four chains" through the intermediary path of financial development. Based on the conclusions of the study, it is recommended that efforts be made in three aspects, namely, technological research and development, financial support and institutional synergy: to strengthen key technologies such as artificial intelligence and blockchain, to improve the digital financial support system, and to optimize the synergistic mechanism between policy and market.

Keywords: digital technology; manufacturing; "four-chain" integration

1. Introduction

Manufacturing is the core of the real economy, and although China has become a major manufacturing country, it still faces challenges such as technological dependence and insufficient innovation. In the context of the complex and changing external environment, it is crucial to promote the deep integration of the digital economy and the real economy, and to realize the synergistic development of the innovation chain, industrial chain, talent

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chain and capital chain. Digital technology as a key breakthrough, its enabling manufacturing "four chains" integration path to be explored. At present, the research on the development of the "four chains" integration, "four chains" integration goal is to break the knowledge, technology, capital, talent, data and other innovation factors in the cross-organizational flow of barriers, through the optimization of the efficiency of the allocation of factors, to promote the rapid agglomeration of multiple factors and efficient circulation[1]. Quantitative analysis found that the regional differences in the coupling and coordinated development of the manufacturing industry "four chains" roughly show an inverted "U" trend of first rising and then falling, mainly from the inter-regional differences [2]. At the same time, the digital economy significantly accelerates the deep integration of the "four chains" of the manufacturing industry, which constitutes the core mechanism to promote the integration of the "four chains" by effectively mitigating the mismatch of capital and labor [3], and the digital economy also shows significant spatial spillover benefits[4].

Most of the existing studies focus on the analysis of individual chains or single dimensions, and lack a systematic exploration of the specific mechanisms and effects of digital technology in promoting the integration of the four chains. Moreover, when analyzing the integration of digital technology and the "four chains", existing studies have neglected the key roles played by government guidance and market mechanisms in this process. Compared with the existing literature, the marginal contributions of this paper are: first, the inclusion of financial development elements into the analytical framework of the "four chains" integration of the manufacturing industry helps to study the internal mechanism of digital technology development on the integration of the "four chains" of the manufacturing industry. Secondly, from the dual perspective of the government and the market, it explores the differences in the regulating effects of the two in the process of "four-chain" integration of manufacturing empowered by digital technology, and gives full play to the roles of the government and the market in the field of manufacturing to provide a theoretical basis.

2. Theoretical analysis and hypothesis study

2.1 The direct impact of digital technology on the integration of the "four chains" of manufacturing

Digital technology directly promotes the deep integration of the "four chains" through the following four aspects: in the innovation chain, big data, artificial intelligence and other technologies accelerate the flow of information and research and development efficiency, and promote the transformation of technological achievements [5]; in the industrial chain, intelligent integration of production, logistics and other links is realized, which significantly improves the efficiency of synergy [6]; in the capital chain, blockchain and other technologies improve the transparency and security of the flow of funds [7]; in the talent chain, the digital platform breaks the geographical restrictions and optimizes the talent allocation efficiency [8]. Overall, digital technology effectively promotes the organic integration of the "four chains" by improving operational efficiency, enhancing synergy and optimizing management transparency. Based on the above analysis, this paper puts forward the following hypotheses:

H1: Digital technologies can directly contribute to the integration of the "four chains" of the manufacturing industry.

2.2 Indirect mechanism of digital technology on the integration of the "four chains" of manufacturing industry

Digital technology provides systematic support for the integration of the "four chains" of the manufacturing industry by promoting the digital transformation of the financial industry [9]. The application of technologies such as big data, artificial intelligence, blockchain and cloud computing has significantly improved the intelligent level of financial services, optimized the efficiency of financial resource allocation, and enhanced the transparency and security of capital flows. This transformation not only provides manufacturing enterprises with more convenient intelligent financing channels and improves the financing environment for innovative activities, but also reduces financing costs by simplifying the process and guarantees the efficient operation of the capital chain. At the same time, financial innovation provides a new support tool for enterprise talent management [10], which promotes the benign interaction between the talent chain and the industrial chain. By improving the efficiency of capital allocation, digital finance effectively promotes the synergistic development of the manufacturing innovation chain, industrial chain, capital chain and talent chain, and creates favorable conditions for the deep integration of the "four chains". This paper puts forward the hypothesis:

H2: Digital technologies can facilitate financial development and "four-chain" convergence in the manufacturing sector.

2.3 Regulatory role

The government plays a key role in promoting the integration of the four chains of manufacturing: on the one hand, it reduces the cost of enterprise transformation through financial subsidies, tax incentives and other policies, and on the other hand, it establishes an innovation platform to promote the synergy of industry, academia and research [11]. In terms of financial support, special loans are set up to ease the pressure on enterprises; in terms of talent cultivation, school-enterprise cooperation is promoted to cultivate digitized talents [12]; meanwhile, the construction of new infrastructures, such as 5G and industrial Internet, is accelerated. This multi-pronged support policy not only solves the practical difficulties of enterprise transformation, but also creates a favorable environment for industry chain collaborative innovation. Based on the above analysis, this paper proposes the hypothesis:

H3: Government support positively moderates the impact of digital technology on the integration of the four chains of manufacturing.

The market mechanism drives the integration of the "four chains" through three core paths: first, demand-pull, consumer preference changes in smart products to form a sustained impetus for industrial upgrading, forcing technological innovation and adjustment of factor configuration; second, competition-driven, enterprises to enhance competitiveness to actively optimize the allocation of innovation resources[13], to promote the industry chain coupled with the innovation chain; third, the platform is empowered to break down the barriers of the industry by digital platforms to build a collaborative network of cross-industry networks. chain synergistic network. These three mechanisms are mutually reinforcing, forming a virtuous cycle of "demand-driven innovation, competition-optimized allocation, and platform-promoted synergy", which provides continuous kinetic energy for the digital transformation of the manufacturing industry:

H4: The level of marketization positively moderates the impact of digital technologies on the integration of the "four chains" of manufacturing.

3. Modeling and Data Description

3.1 Measurement modeling

This paper uses the double fixed-effects model, the mediating-effects model and the moderating-effects model to study the role of digital technology in empowering the traditional manufacturing industry to integrate the "four chains".

(1) *Benchmark regression model.* In order to explore the impact of digital technology on the integration of the "four chains" of manufacturing industry, a panel two-way fixed-effects model is constructed as in equation (1).

$$Fcf_{it} = \alpha_0 + \alpha_1 Dig_{it} + \sum_j \alpha j Control_{jit} + \mu_i + v_i + \varepsilon_{it} \tag{1}$$

i,t and j denote region, year and jth control variable; Fcf_{it} denotes the degree of integration of the "four chains" of manufacturing; Dig_{it} denotes the level of digital technology; $Control_{jit}$ denotes the control variable; ε_{it} denotes the random error term; α_0 , α_1 and α_j denote the banded coefficients; μ_{it} denotes the individual fixed effects; and v_{it} denotes the time-fixed effects.

(2) *Mediating effects modeling.* In order to verify whether there is an indirect effect mechanism of digital technology on the integration of the manufacturing industry "four chains" chain, drawing on the research of Wen Zhonglin [14], to construct a mediation effect model such as formula (2), (3) to test.

$$Med_{it} = \beta_0 + \beta_1 Dig_{it} + \sum_j \beta_j Control_{jit} + \mu_i + v_i + \varepsilon_{it} \tag{2}$$

$$Fcf_{it} = \gamma_0 + \gamma_1 Dig_{it} + \gamma_2 Med_{it} + \sum_j \gamma_j Control_{jit} + \mu_i + v_i + \varepsilon_{it} \tag{3}$$

where Medit denotes the mediating variable.

(3) *Moderating effects model.* In order to study the impact of government support and marketization on the integration of digital technology and the "four chains", the following model is constructed by adding the interaction term between digital technology and regulatory variables on the basis of equation (1):

$$Fcf_{it} = \eta_0 + \eta_1 Dig_{it} + \eta_2 Z_{it} + \eta_3 Dig_{it} \times Z_{it} + \sum_j \eta_j Control_{jit} + \mu_i + v_i + \varepsilon_{it} \tag{4}$$

Where Z_{it} denotes the moderating variables. It includes government support (Gov) and marketization level (Mar) In addition, before verifying the moderating effects, this paper centers the interaction term indicators.

3.2 Variable Selection and Description

(1)*Explained Variables.* The degree of integration of the "four chains" of the manufacturing industry. According to the research of Qi Ping and others, the evaluation index system of the degree of integration of the "four chains" of manufacturing industry is constructed, including 4 subsystems, 11 first-level indicators and 20 second-level indicators. [3].After the construction of the manufacturing industry "four chains" integration degree evaluation index system, the comprehensive use of entropy value method, coupling degree model and coupling coordination degree model to measure the manufacturing industry "four chains" integration degree. Specifically:

$$T=\sqrt{C\times T} \tag{5}$$

$$C=\left\{\frac{\dfrac{U_1\times U_2\times U_3\times U_4}{\left[U_1+U_2+U_3+U_4\right]^4}}{4}\right\}^{\frac{1}{4}} \tag{6}$$

$$T=\alpha U_1+\beta U_2+\gamma U_3+\theta U_4 \tag{7}$$

In Eq. (5), D denotes the coupling degree among the four chains, T denotes the comprehensive coordination index among the four chains, and U_1 , U_2 , U_3 and U_4 are the comprehensive evaluation indexes of the innovation chain, industrial chain, talent chain and capital chain, respectively. All of them are calculated by entropy method. $\alpha\beta\gamma$, and θ are coefficients to be determined, and $\alpha+\beta+\gamma+\theta=1$ $\alpha=\beta=\gamma=\theta=0.25$

(2) *Explanatory variables* .Digital technology level. Drawing on Jia Weifeng's research [15], the entropy value method is further adopted to determine the weights of the evaluation indicators of digital basic technology and digital application technology, and calculate their comprehensive development level.

(3) *Mediating variables* .Financial development (Fd).total deposits and loans are used to indicate the level of financial development.

(4) *Moderating variables* .The level of government support (Gov) is expressed by using local financial expenditure on science and technology. The level of marketization (Mar) is expressed using the marketization index.

(5) *Control variables.* Foreign investment (Fi) is expressed using regional foreign capitalization. Water resource utilization (Res) is expressed using industrial water consumption. Education level (Edu) is expressed using the share of local fiscal expenditure on education in regional GDP. Transportation conditions (Rm) are expressed using the number of road miles.

4. Empirical analysis

4.1 Benchmark regression

Table 1 reports the results of the baseline regression of digital technology affecting the integration of the "four chains" of manufacturing. In columns (1) and (2), the regression coefficients for digital technology (Dig) are 0.079 and 0.073, respectively; both are significant at the 1 per cent level. At this point, hypothesis 1 is certified.

Table 1 Direct effect regression results

variant	(1)	(2)
	Fcf	Fcf
Dig	0.079 ***	0.073 ***
	(4.544)	(4.604)
-cons	0.496 ***	0.423 ***
	(48.700)	(15.091)
control variable		Yes
Province fixed	Yes	Yes
Year fixed	Yes	Yes
N	330	330
R2	0.957	0.965

4.2 Robustness Tests

Table 2 shows the results of the robustness test. Among them, column (1) is the test result of excluding the municipality directly under the central government sample. The results show that the regression coefficients of digital technology have not been significantly changed. Column (2) shows the test results of the reduced-tail treatment. After regressing all sample data again after a two-way 1% shrinkage treatment, the results show that the regression coefficient of digital technology is still positive at the 1% significance level. Column (3) shows the results of the baseline regression by shortening the time horizon to 2013-2022. The results show that digital technology still promotes the integration of the four chains of manufacturing. This indicates the robustness of the benchmark regression results.

Table 2 Robustness test results

variant	Excluding municipalities	shrinkage treatment	Reduction of time years
	(1)	(2)	(3)
	Fcf	Fcf	Fcf
Dig	0.090 ***	0.077 ***	0.053***
	(4.662)	(4.586)	(3.873)
control variable	Yes	Yes	Yes
Province fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
-cons	0.175 ***	0.430 ***	0.468 ***
	(5.092)	(14.974)	(18.919)
N	286	330	300
R2	0.956	0.965	0.977

4.3 Analysis of mediating effects

The results of the empirical testing of the transmission mechanism of digital technology through financial development to influence the integration of the "four chains" of the manufacturing industry using the mediation effect model are presented in table 3. Columns (2) and (3) show the results of the empirical test of the mediating role of financial development between digital technology and the "four chains" of manufacturing industry. Column (2) shows that the regression coefficient of digital technology on financial development is significant at the 1% level, indicating that digital technology can promote the development of finance. Column (3) is the regression result of adding the mediating variable of financial development, which can be seen that the regression coefficient of digital technology decreases from 0.073 to 0.056, while the regression coefficient of financial development is 0.004, which proves that the financial development plays a role in the "four-chain" integration of the manufacturing industry with the digital technology, and that financial development plays a role in the "four-chain" integration of the manufacturing industry. This proves that financial development plays a partial intermediary role in the process of "four chains" integration of digital technology-enabled manufacturing industry, and hypothesis 2 is confirmed.

Table 3 Mediating effects test

variant	(1)	(2)	(3)
	Fcf	Fd	Fcf
Dig	0.073 ***	4.648 ***	0.056 ***
	(4.604)	(7.397)	(3.262)
Fd			0.004**
			(2.474)

control variable	be	be	be
-*cons*	0.423 ***	8.878 ***	0.391 ***
	(15.091)	(8.005)	(12.697)
Province fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
N	330	330	330
R2	0.965	0.960	0.966

4.4 Analysis of moderating effects

Table 4 reports the results of the regressions with government support and marketization process as moderating variables. Columns (1) and (2) show the regression results with the inclusion of the interaction terms of government support, digital technology and government support, respectively. In column (1), the regression coefficient of government support is significantly positive at the 1% statistical level, indicating that government support significantly promotes the development of "four chains" integration in manufacturing. From the interaction coefficient, the interaction coefficient between digital technology and government support in column (2) is 0.024, and it is significant at 1% statistical level, which indicates that the positive effect of digital technology on the integration of the "four chains" of manufacturing industry is enhanced under the increase of government support, i.e., the government support positively regulates the digital technology to empower the manufacturing industry. That is, government support positively regulates the direct path of the "four chains" integration of digital technology to empower the manufacturing industry, and hypothesis 3 is confirmed.

Columns (3) and (4) show the regression results of adding the interaction terms of marketization level, digital technology and marketization level, respectively. The result of column (3) shows that the regression coefficient of marketization level is significantly positive at 5% statistical level, which indicates that the marketization process enhances the development of the "four chains" integration of manufacturing industry. From the interaction coefficient, the interaction coefficient between digital technology and marketization level in column (4) is 0.016, and it is significant at 1% statistical level, which indicates that the marketization level positively regulates the direct path of digital technology empowering the integration of the four chains of the manufacturing industry, and hypothesis 4 is confirmed.

Table 4 Moderating effects test

variant	(1)	(2)	(3)	(4)
	Fcf	Fcf	Fcf	Fcf
Dig	0.054**	0.030*	0.075 ***	0.048**
	(3.658)	(1.821)	(4.728)	(2.593)
Gov	0.027 ***	0.028 ***		
	(7.832)	(8.034)		
Dig*Gov		0.024 ***		
		(2.772)		
Mar			0.005**	0.005 ***
			(2.231)	(2.629)
Dig*Mar				0.016 ***
				(2.745)
control variable	Yes	Yes	Yes	Yes
-*cons*	0.298 ***	0.308 ***	0.401***	0.413 ***
	(9.909)	(10.288)	(13.507)	(13.916)
Province fixed	Yes	Yes	Yes	Yes

Year fixed	Yes	Yes	Yes	Yes
N	330	330	330	330
R2	0.971	0.972	0.966	0.966

5. Conclusions and Recommendations

This paper builds a theoretical framework of digital technology enabling manufacturing "four chains" integration, empirically examines the direct and indirect impact mechanisms of digital technology on manufacturing "four chains" integration, and further explores the role of the government and the market in the mechanism. The specific conclusions are as follows (1) Digital technology has a significant role in promoting the integration of the "four chains" of manufacturing industry. (2) Digital technology not only directly enhances the degree of integration of the four chains of manufacturing industry, but also realizes the systematic empowerment of the four chains of manufacturing industry through the intermediary path of financial development. (3)The government and market can promote the integration of digital technology into the manufacturing industry's "four chains".

Based on the above conclusions, the policy insights of this paper are: (1) Increase investment in digital technology R&D and application. The government should increase its support for key technologies such as artificial intelligence, big data, and 5G, and promote collaborative innovation among industry, academia, and research institutes through research subsidies, tax incentives, and other measures. Enterprises need to strengthen the application of digital technologies, optimize production processes and management models, and enhance their innovation capacity and competitiveness. (2) Optimize financial support and reduce transformation costs. The government can reduce the financial pressure on enterprises through special funds, low-interest loans and financing guarantees, especially helping technology start-ups. Financial institutions should innovate products and services to help the manufacturing industry digitize and upgrade. (3) Strengthen policy support and market incentives. The government should increase financial support and tax incentives, focusing on assisting technology research and development and infrastructure, to help enterprises break through the transformation bottlenecks. At the same time, build industry platforms to promote collaboration, optimize financial products to reduce the difficulty of financing for SMEs, and promote accurate funding to support digital upgrading and accelerate the integration of the "four chains"

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Research on the Impact of Strategic Flexibility on Advanced Manufacturing Enterprises in China: The Mediating Role of Dynamic Capability and the Regulating Role of Resource Redundancy

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Abstract. With the intensification of competition in today's world and the deepening impact of globalization and anti-globalization, enterprises are also facing uncertain challenges in the process of business management. For manufacturing enterprises, transitioning to service-oriented is an important strategy to adapt to market demands and enhance their competitiveness. Although it is widely believed that servitization is an important driving force for manufacturing to enhance its competitiveness, there is still controversy in the academic community about how to achieve servitization. By consulting relevant literature and understanding the introduction of organizational flexibility, combined with the uncertain environment faced by enterprises, this study mainly explores the impact of organizational flexibility on the servitization of advanced manufacturing enterprises, and incorporates dynamic capability theory to analyze the mechanism of how organizational flexibility affects servitization. At the same time, incorporating redundant organizational resources as moderating variables into the framework to verify the moderating mechanism of the impact of dynamic capabilities on enterprise servitization. This study used fixed effects regression analysis to analyze data from 246 Chinese listed advanced manufacturing enterprises from 2018 to 2022, in order to verify the impact and mechanism of organizational flexibility on the servitization of advanced manufacturing enterprises. The results indicate that organizational flexibility has a positive impact on enterprise servitization; Dynamic capabilities play a mediating role in the relationship between organizational flexibility and enterprise servitization; Unabsorbed redundant resources play a positive moderating role between dynamic capabilities and enterprise servitization; The absorption of redundant resources plays a negative moderating role between dynamic capabilities and enterprise servitization. The research results aim to provide some suggestions on how advanced manufacturing enterprises can transform into service-oriented enterprises when facing uncertain environments and promote the continuous survival and development of the manufacturing industry under uncertain environmental conditions.

Keywords. Organizational flexibility, dynamic capability, servitization, absorbed redundant resources, unabsorbed redundant resources

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1 Introduction

With the continuous slowdown of economic growth in today's world, various economies are facing numerous challenges. At the same time, geopolitical and other factors are intertwined, exacerbating economic uncertainty. These factors have had a great impact on enterprises, making the business environment more complex and turbulent. Meanwhile, as a major component of the national economy, manufacturing plays an important role in promoting national development and technological innovation [1]. Manufacturing is the foundation of the real economy and the cornerstone of economic development [2]. However, China's manufacturing industry is currently facing the problem of large scale and insufficient innovation [3]. In addition, the constantly changing market demand and the thriving development of the service economy have also forced manufacturing companies to seek change [4]. In order to seize the opportunities of the future manufacturing industry and cope with the challenges inside and outside the manufacturing industry, the Chinese government has taken a series of measures, with the main direction being the service-oriented transformation of the manufacturing industry [5]. For example, the Chinese government's "Made in China 2025" strategy launched in 2015 has promoted the transformation of production-oriented manufacturing to service-oriented manufacturing, and gradually shifted from "Made in China" to "Innovative Manufacturing in China". Faced with complex internal and external environments, the service-oriented transformation of enterprises in strategic competition is becoming a significant feature of innovative manufacturing [6]. Servitization is a process of transformation and upgrading, in which manufacturing enterprises add services to their core products, providing customers with innovative, high-value integrated solutions and enhancing the competitive value of the enterprise [7]. Although servitization has different definitions in various literature, the commonality is that manufacturing companies need to be customer-centric and have sufficient innovation capabilities to expand their business [8]. With the application of servitization in manufacturing enterprises, the effective allocation of resources through servitization has been widely recognized as an effective way to enhance global market competitiveness.

Servitization refers to the manufacturing industry bundling services and products together to create value, which has been considered a highly competitive strategy [9]. However, in real business practice, manufacturing enterprises also face many challenges. Internally, they will face issues such as system formulation, costs, and talent, while externally, they will be influenced by policy trends and complex international situations. The complexity of the internal and external environment of manufacturing enterprises also represents a certain degree of uncertainty in the strategy of service-oriented manufacturing. At this time, it is necessary to increase the flexibility of service-oriented strategy to cope with internal and external challenges. Aaker and Mascarenhas argue that strategic flexibility is the ability of an organization to adapt to significant, uncertain, and rapidly occurring environmental changes that have a significant impact on organizational performance [10]. In the process of service-oriented manufacturing, it is possible to ensure the smooth implementation of the service-oriented strategy of manufacturing enterprises by adjusting the strategy according to changes in the internal and external environment. Therefore, this article draws on the research of Yeniaras, Di Benedetto, and Dayan on the positive impact of organizational flexibility on servitization [11], as well as the research of Bula and Ziebicki on the division of organizational flexibility [12]. At the same time, considering the strong representativeness and high degree of servitization of advanced manufacturing enterprises, it is decided to analyze the impact of strategic flexibility on servitization of advanced manufacturing enterprises, in order to explore how manufacturing enterprises can achieve successful servitization through strategic flexibility.

White and Feng (1999) argue that servitization is a dynamic process in which the business model of manufacturing enterprises shifts from a traditional product centric approach to a service-oriented approach [13]. Service oriented transformation is a process that requires manufacturing enterprises to develop dynamic capabilities to support the process of change and overcome various challenges caused by sustained external environmental turbulence [7][14]. Teece et al. (1997) argue that dynamic capabilities focus on continuously integrating and reconfiguring resources to ensure their competitive advantage [15]. In the face of internal and external challenges, to ensure the smooth progress of service-oriented manufacturing enterprises, they need to develop dynamic capabilities to adjust and allocate enterprise resources to cope with the challenges. In addition, this study also draws on the research of Teece et al. (1997), which suggests that the relationship between strategy and dynamic capability can be summarized as dynamic capability being an important component of strategic management, and dynamic capability being able to influence the formulation and implementation of strategic management [15]. Based on the relationship between strategic flexibility, dynamic capability, and manufacturing servitization, this article uses dynamic capability as a mediating variable to explore the impact of strategic flexibility on the implementation path of manufacturing servitization.

Dynamic capability refers to the ability of an enterprise to integrate, reconfigure, and update internal and external resources and capabilities in a rapidly changing environment, in order to respond to challenges that arise over time and maintain a competitive advantage [15][16]. Both internal and external resources need to support the operation and development of a company. External resources are the foundation for a company to gain competitive advantage, while internal resources are the basis for driving effective decision-making in the enterprise [17]. This study focuses on the role of internal resources in the relationship between dynamic capabilities and manufacturing servitization, dividing internal resources into absorbed redundant resources and unabsorbed redundant resources. Redundant resources, also known as idle resources, can provide multiple functions such as buffering, adapting to changes, and promoting innovation. They refer to resources in an organization that exceed what is needed to maintain a certain level of output [18]. According to its own liquidity and flexibility of use, redundant resources, as potential resources within the enterprise, can enhance its competitiveness and solve the problem of resource scarcity. At the same time, inappropriate redundant resources can also have a negative impact on the enterprise. Considering the relationship between dynamic capabilities and redundant resources, and combining with the resource-based view, this article incorporates redundant resources into the model to explore their role in the relationship between dynamic capabilities and manufacturing servitization from a resource perspective.

This study is of great significance. Firstly, it investigates the relationship between strategic flexibility and successful servitization of enterprises. From the perspective of strategic management, it analyzes the realistic path to achieving successful servitization, providing a new perspective for manufacturing enterprises to achieve successful servitization, enriching the relevant literature on how manufacturing enterprises can transform into service-oriented enterprises, and filling the current research gap. Secondly, this study also explored the moderating role of redundant resources between dynamic capabilities and servitization, delving into and revealing the potential value of redundant resources in this context from a resource perspective, enriching the resource-based view.

In view of this, this article selects data from 246 advanced manufacturing enterprises listed on the A-share market in China from 2018 to 2022 as research samples to analyze the mechanism of "strategic flexibility dynamic capability advanced manufacturing enterprise servitization". At the same time, the redundant resources within the enterprise are divided into absorbed redundant resources and unabsorbed redundant resources, aiming to reveal the impact of redundant resources between dynamic capabilities and manufacturing servitization.

2 Literature review

2.1 Strategic Flexibility

The academic community has given high attention to strategic flexibility, but there are unique perspectives on its definition. Bo Dong (2024) believes that strategic flexibility refers to the ability of enterprises to flexibly transform, quickly adapt, and respond to environmental changes[19]; Aaker and Mascarenhas (1984) argue that strategic flexibility is the ability of an organization to adapt to significant, uncertain, and rapidly occurring environmental changes, which have a significant impact on organizational performance[10]; Kafetzopoulos (2023) believes that strategic flexibility is the ability of a company to reconfigure internal resources and quickly adapt to market changes[20]. Drawing on the definition of strategic flexibility by relevant scholars, this article defines strategic flexibility as the ability of an enterprise to quickly adapt to changes and maintain its competitive advantage by continuously allocating resources in the face of uncertain and complex external environments. Strategic flexibility, as a dynamic capability, optimizes an enterprise's operational model to adapt to high uncertainty environments by flexibly reconfiguring and adjusting organizational resources and processes [21].

Strategic flexibility is considered a key factor in gaining competitive advantage in a dynamic market environment [22]. Strategic flexibility enables manufacturing enterprises to effectively respond to external changes by flexibly reconfiguring resources, processes, and strategies, thereby enhancing their competitive advantage and innovation capabilities [23]. In summary, strategic flexibility enables enterprises to continuously adjust their business and operational models to adapt to market conditions in turbulent environments, thereby maintaining the survival and development of the enterprise.

2.2 Servitization

Servitization was first proposed by Vandermerwe and Rada (1988), who defined it as the process by which businesses enhance the value of their core products by adding service content [24]. This process is called "servitization" and emphasizes the importance of services in modern business, especially in creating and maintaining customer relationships. Subsequently, the academic community further elaborated on the concept of servitization. Among them, White&Feng (1999) believed that servitization is a dynamic process, which refers to the change of suppliers from product centered to service centered [13]; Reiskin et al. (1999) argue that servitization is the shift of a company's focus from simply selling products to providing services to meet customers' functional needs [25]. Based on previous academic research, this article defines servitization as the ability of manufacturers to innovate products and provide added value through services.

Servitization has enhanced the innovation capability of manufacturing enterprises in the field, and manufacturing enterprises can improve their competitiveness and market responsiveness through service innovation [26]. So far, there is no established standard in academia for measuring successful servitization. Considering that measuring servitization involves complex dimensions, this article explores successful servitization from both financial and non-financial perspectives [11].

2.3 Dynamic Capability

Dynamic capability refers to the ability of a company to maintain its competitive advantage by integrating, reconfiguration ability, and updating internal and external resources in a turbulent environment [15]. By defining dynamic capabilities, this study divides them into reconfiguration ability, learning ability, and coordination and integration ability. The functionality of dynamic capabilities is further developed based on the Resource Based View (RBV). The resource-based view advocates continuously accumulating unique resources and capabilities to enable enterprises to gain competitive advantages [27]. However, in today's volatile market environment, simply accumulating resources is not enough to ensure the survival and development of enterprises. Therefore, enterprises need dynamic capabilities to acquire, assimilate, and reconfigure resources to adapt to the constantly changing external environment and gain competitive advantage [28].

2.4 Redundant Resources

From the perspective of resource-based view, enterprises gain competitive advantage through the accumulation of their own unique resources. Stan et al. (2014) argue that redundant resources can provide multiple functions such as buffering, adapting to changes, and promoting innovation, referring to resources in an organization that exceed what is needed to maintain a certain level of output[18]; Li et al. (2024) argue that redundant resources are resources that exceed the daily operational needs of a business and will play a certain role in the future[17]. Based on the comprehensive literature, redundant resources refer to the resources left after maintaining the normal operation of an enterprise. These resources provide buffering and promote innovation to adapt to external environmental changes and enhance the competitiveness of the enterprise.

According to the mobility and flexibility of resource utilization, Cyert and March (1963) argue that redundant resources can be divided into absorbed redundant resources and unabsorbed redundant resources [29]. Redundant resources help enhance a company's innovation capability, providing a buffer and a means of change when facing future challenges. However, inappropriate redundant resources can also have a negative impact on the company. Among them, unabsorbed redundant resources are unused flowing resources, which are relatively easy to allocate to organizational processes. Absorbed redundant resources refer to resources that have already been utilized by an organization, but are difficult to reconfigure and can result in excess losses [30]. This study incorporates redundant resources into the model to explore the relationship between absorbed redundant resources and unabsorbed redundant resources in dynamic capabilities and manufacturing enterprise servitization, respectively.

3 **Research Hypothesis**

3.1 Strategic flexibility and servitization

Strategic flexibility refers to the ability of enterprises to flexibly transform, quickly adapt, and respond to environmental changes [19]. Strategic flexibility enables enterprises to adjust their strategies to adapt to changes in the external environment, thereby maintaining sustained competitiveness and long-term development. Servitization is often regarded as a strategic update [14], and the service-oriented transformation of manufacturing enterprises is the process of shifting their strategy from product centric to service-oriented, which is a manifestation of strategic flexibility. With the intensification of market turbulence and the continuous increase in services provided by manufacturing enterprises for their products, the servitization of advanced manufacturing has become a key business strategy in recent years [31]. The driving effect of strategic flexibility on the servitization of manufacturing enterprises is manifested in two aspects: firstly, enhancing market adaptability. When the market environment is turbulent, market demand is constantly changing, and customer expectations and requirements are also constantly changing [32]. Strategic flexibility enables manufacturing enterprises to adjust service content and service models in a timely manner to meet the diversity and variability of market demand. Secondly, optimize resource allocation. In the process of service-oriented advanced manufacturing, resources such as technology, capital, and personnel often need to be reconfigured. Strategic flexibility can enable enterprises to flexibly allocate resources at different times, so that enterprise resources will not be overly concentrated and wasted. Yeniaras, Di Benedetto, and Dayan (2021) argue that organizational flexibility has a positive impact on servitization, and strategic flexibility is a dimension of organizational flexibility [11]. Based on this, this article proposes hypothesis H1. Because this article aims to intuitively understand the impact of strategic flexibility on the servitization of advanced manufacturing enterprises, regression analysis is used to verify whether H1 holds true.

H1: The flexibility of enterprise strategy plays a positive role in the service-oriented development of advanced manufacturing enterprises.

3.2 The mediating role of dynamic capabilities

Teece et al. (1997) defined dynamic capability as the ability to coordinate, integrate, and reconfigure an enterprise's internal and external resources to adapt to a constantly changing external environment, thereby achieving sustained competitiveness[15]. By its definition, it can be divided into two categories: reaction and coordination integration. Strategic flexibility can promote the servitization of advanced manufacturing industry through dynamic capabilities.

Strategic flexibility can enhance the dynamic capabilities of enterprises in the following ways: firstly, strategic flexibility can enhance the responsiveness of enterprises. Strategic flexibility encompasses both resource flexibility and coordination flexibility [33]. Coordination flexibility can quickly adjust its strategy and allocate its resources according to market changes [34]. Strategic flexibility can continuously change a company's strategy in response to market changes, policy adjustments, and other factors, enabling the company to adapt to future or present changes. Secondly, strategic flexibility can enhance the ability of enterprises to coordinate and integrate their resources. Strategic flexibility itself has the ability to reconfigure enterprise resources and strategies to adapt to market demand [35]. Among them, resource flexibility enables enterprises to quickly adjust their strategies and timely apply other forms of resources [34].

The dynamic capability of enterprises plays a promoting role in the service-oriented manufacturing industry. Dynamic capability is a key driving factor for servitization [36]. This study divides dynamic abilities into three aspects: coordination and integration ability, learning ability, and reconfiguration ability, based on the research of Teece et al. (1997) [15]. Kanninen et al. (2017) argue that these aspects of dynamic capabilities play important roles in various stages of enterprise servitization[37]. The positive impact of dynamic capabilities on servitization is manifested in: firstly, coordination and integration capabilities can help enterprises coordinate internal resources at different stages of servitization, ensuring collaboration and resource integration in all aspects of the servitization transformation process. Secondly, learning ability enables enterprises to continuously transform new knowledge and skills into internal capabilities during the process of service-oriented transformation. Finally, the ability to refactor can help adjust and reconfigure resources to cope with external changes and internal demand transformations during enterprise servitization. Therefore, this article proposes hypothesis H2. Because this article aims to visually verify the relationship between strategic flexibility, dynamic capabilities, and advanced manufacturing enterprise servitization, Baron & Kenny method is used to conduct stepwise regression analysis to test whether H2 holds true.

H2: Dynamic capabilities play a mediating role between strategic flexibility and advanced manufacturing servitization.

3.3 The regulatory role of redundant resources

Redundant resources, also known as idle resources, refer to the resources remaining after the normal operation of an enterprise consumes relevant resources, including manpower, equipment, funds, etc. [18]. Drawing on the research of Cyert and March (1963), this paper divides redundant resources into absorbed redundant resources and unabsorbed redundant resources [29]. Among them, unabsorbed redundant resources are unused flowing resources that can be applied to various aspects required by the enterprise at any time. Absorbed redundant resources refer to the remaining resources that have already been utilized, which consume and are inconvenient for enterprises to reconfigure, including surplus equipment, surplus personnel, etc. [30]. Dynamic capabilities promote the servitization of manufacturing enterprises by coordinating, integrating, and reconfiguration internal and external resources. The resource-based view emphasizes that a company's competitive advantage not only comes from the external market environment, but more importantly, from unique and difficult to imitate resources and capabilities within the company. There is a certain correlation between dynamic capabilities and redundant resources. Enterprises can enhance their dynamic capabilities to make internal resources more effectively utilized. Combining the resource-based view, this article aims to explore the impact of internal resources on the servitization of advanced manufacturing enterprises through the dynamic capabilities of enterprises, that is, the moderating effect of redundant resources between dynamic capabilities and servitization of advanced manufacturing enterprises.

Highly liquid and unabsorbed redundant resources are important buffer resources for enterprises to cope with environmental turbulence. From the perspective of resource support, unabsorbed redundant resources provide support for service-oriented innovation in advanced manufacturing enterprises. Services have the characteristics of intangibility, heterogeneity, and variability, which makes it difficult for enterprises to effectively maintain their inherent service models. However, without absorbing redundant resources, advanced manufacturing enterprises can continuously update their service models based on more flexibility and autonomy. Not absorbing redundant resources allows enterprises to invest resources into more forward-looking service projects, which enhances their trial and error and service innovation capabilities [38].

Absorbed redundant resources refer to idle resources within a specific program of an enterprise. The specificity of absorbed redundant resources limits the coordination of resources by enterprises in the face of changes, which may miss the optimal market response time. At the same time, the absorption of redundant resources also has path dependence, which enables enterprises to connect resources within their existing business models. However, due to the influence of inherent thinking, it has a negative effect on the process reengineering and updating of service models. In summary, this article proposes hypotheses H3 and H4. This article explores the impact of the interaction between dynamic capabilities and redundant resources on the servitization of advanced manufacturing enterprises, aiming to test the validity of hypotheses H3 and H4. Therefore, regression analysis is used to visually demonstrate the moderating effect.

H3: Unabsorbed redundant resources can be flexibly applied, therefore, when the dynamic capabilities of enterprises promote the servitization of advanced manufacturing enterprises by adjusting internal resources, it will play a positive regulatory role.

H4: The absorbed redundant resources have a specific program, so when the dynamic capability of an enterprise promotes the servitization of advanced manufacturing enterprises by adjusting internal resources, it will play a negative regulatory role.

4. Research Design

4.1 Sample and Data Collection

This article selects enterprises in China's A-share listed companies that belong to the advanced manufacturing industry as research samples. In this article, advanced manufacturing enterprises are classified based on the advanced level, innovation, breadth of technology application, and modernization level of industrial development of manufacturing technology. At the same time, referring to Tian et al. (2023) classification for advanced manufacturing industries, and combining the use of advanced technology to upgrade traditional manufacturing industries into advanced manufacturing enterprises as the research object, after considering the availability and operability of data, the final six industries of advanced manufacturing enterprises are determined to include general equipment manufacturing, specialized equipment manufacturing, railway, ship, aerospace and other transportation equipment manufacturing, computer, communication and other electronic equipment manufacturing, electrical machinery and equipment manufacturing, and instrumentation manufacturing[39]. With the increasingly volatile market environment in today's world, strategic flexibility is considered a key determinant for gaining competitive advantage in turbulent markets [23]. To ensure the timeliness of our research, this article have chosen the sample interval from 2018 to 2022. Considering the time lag effect of strategic flexibility on servitization, this study lagged the data of the independent variable strategic flexibility by one period. Therefore, this paper chose data from 2018-2021 as the explanatory variable and data from 2019-2022 as the outcome variable. All the data comes from third-party commercial databases, including Wind and CSMAR.

In this study, this article processed the raw data as follows: (1) excluded enterprise data from non advanced manufacturing industries mentioned above; (2) Exclude enterprise data with missing key indicators; (3) Perform 1% Winsorize truncation on all variables; (4) Lagged the independent variable strategic flexibility by one period; (5) Exclude data from ST, * ST, and companies delisted during the study sample period. Finally, a total of 1230 observation data were obtained from 246 companies. At the same time, Stata 18 statistical software was used for data analysis in this study, mainly for descriptive statistical analysis and regression analysis. All data processing steps are completed in this software.

4.2 Variables and Measurements

4.2.1 Explanatory variables

Strategic Flexibility (SF): This article draws on some of Nadkarni and Narayanan's (2007) research results on strategic flexibility and combines the dynamic nature of strategic flexibility[40]. Finally, this article uses the degree of annual change in enterprise resources as an indicator to measure the strategic flexibility of enterprises. Firstly, this article selects R&D investment intensity, advertising investment intensity, and asset intensity as indicators of the resources to be allocated by the enterprise. Among them, this article uses the ratio of a company's R&D expenditure for that year to its total revenue for that year, which is commonly used to measure the intensity of a company's R&D investment [41]; The advertising R&D intensity of a company is measured by the ratio of its annual advertising expenditure to its total revenue [42]; The asset intensity of a company is measured by its total assets and total revenue for that year [43]. At the same time, the measurement of strategic flexibility requires variance standardization of three indicators. In order to smoothly standardize the variance, the sample intervals for these three indicators are from 2017 to 2023.

Finally, using 2018, 2019, 2020, 2021, and 2022 as base periods T, calculate the variances of the three indicators over a period of three years (T-1, T+1). Normalize the variances obtained based on the industry's standardized level absolute value, and then add the absolute values of the standardized variances of the three indicators to obtain the level of strategic flexibility of the enterprise.

4.2.2 Intermediary variable

The mediating variable in this article is dynamic capability (Cdc). Drawing on the research results of Teece et al. (1997) on dynamic capabilities, dynamic capabilities are divided into three sub dimensions: reconfiguration capability, learning capability, and coordination and integration capability[15]. On this basis, referring to the calculation method of Jia et al. (2023) for dynamic capability indicators, this paper calculates the dynamic capability of enterprises by using the entropy method to determine the weights of each indicator[44].

Entropy method is a commonly used multi index comprehensive evaluation method, mainly used to process multidimensional data, especially when evaluating the contribution of different factors to a certain problem. It is based on the principle of information entropy and aims to quantify the degree of dispersion of various indicators, thereby measuring the importance of each indicator. The entropy method has steps of standardizing data, calculating entropy, and calculating weights. When calculating weights, the weight of each indicator is calculated based on the size of the entropy value. The larger the entropy value, the more uniform the information of the indicator and the lower the weight; The smaller the entropy value, the more concentrated the information, and the higher the weight. The entropy method has strong objectivity and can effectively avoid the interference of subjective factors on the evaluation results. It is widely used in fields such as social and economic analysis.

Reconfiguration ability (REC): According to the study by Zhan et al., this article uses the proportion of intangible assets to total assets to measure REC [13]. Among them, intangible assets refer to long-term assets that do not have a physical form but can bring economic benefits to the enterprise, including patents, trademarks, copyrights, goodwill, etc.

Learning ability (LEN): Referring to the study by Zhao et al. (2012), this article uses the proportion of employees with a bachelor's degree or higher to measure a company's learning ability[45].

Coordination and Integration Capability (CPI): According to the research of Sheng and Jiang (2018), this study uses the total asset turnover rate to measure the coordination and integration capability of enterprises[46].

4.2.3 Adjusting variables

Redundant resources are the moderating variables in this study. Redundant variables can be divided into two dimensions: unabsorbed redundant resources (US) and absorbed redundant resources (AS) [28]. This article draws on the research of Wang et al. (2017) and uses the quick ratio as an indicator to measure the unabsorbed redundant resources [47]. This article has absorbed redundant resources and measured it by the ratio of sales, general and administrative expenses to sales revenue based on Marlin and Geiger's (2015) research[48].

4.2.4 Result variable

The success of servitization covers two aspects, namely financial and non-financial aspects [11]. It is generally believed that financial success usually refers to the degree to which a company achieves or exceeds its set economic goals, while non-financial success usually refers to the company's achievements and performance beyond economic indicators, which can be seen through the proportion of business personnel served by the company. On this basis, this article further uses the entropy method to measure the comprehensive indicators of servitization. The detailed description of this indicator is as follows:

Financial Service Success (SVF): This article measures the proportion of service business revenue within listed companies. From the perspective of company output, servitization can be measured by the proportion of sales revenue from service products to total sales revenue [49][50].

Personnel Service Success (SVP): The proportion of service personnel in the business. According to previous research, the trend of labor shifting from the manufacturing sector to the service sector is constantly strengthening [51]. Due to the strong dependence on personnel in the service, we use the ratio of non productive employees to the total number of employees to measure the success of personnel services instead of the proportion of service business personnel. Non productive employees are defined in this article as individuals who are not engaged in technical, service, system, financial, maintenance, or other service work.

4.2.5 Control variables

Based on the research content of this article and in conjunction with recognized literature [52], this article uses firm size (Size), financial leverage (LEV), and firm nature (EN) as control variables. Among them, the scale of the enterprise is measured by taking the logarithm of the total assets of the enterprise; Financial leverage is measured by the asset liability ratio; For the nature of the enterprise, this article sets it as a dummy variable. If the enterprise is a state-owned enterprise, its value is 1, otherwise it is 0. In the dataset of this article, there are 71 state-owned enterprises and 175 non-state-owned enterprises.

4.3 Model Setting

This article constructs an empirical econometric model to test research hypotheses and uses hierarchical regression to conduct empirical testing. The hierarchical regression method is equally applicable for testing mediation and moderation effects, where the interaction term between mediation and moderation variables should be added when testing moderation effects. The specific regression model constructed in this study is as follows:

$$\mathbf{Servitization}_{i,t}=\alpha_1+\alpha_2\mathbf{SF}_{i,t}+\alpha_3\mathbf{Control}_{i,t}+\varepsilon_{i,t} \quad \textbf{(M1)}$$

$$\mathbf{Cdc}_{i,t}=\beta_1+\beta_2\mathbf{SF}_{i,t}+\beta_3\mathbf{Control}_{i,t}+\varepsilon_{i,t} \quad \textbf{(M2)}$$

$$\mathbf{Servitization}_{i,t}=\gamma_1+\gamma_2\mathbf{SF}_{i,t}+\gamma_3\mathbf{Cdc}_{i,t}+\gamma_4\mathbf{Control}_{i,t}+\varepsilon_{i,t} \quad \textbf{(M3)}$$

$$\mathbf{Servitization}_{i,t}=\theta_1+\theta_2\mathbf{Cdc}_{i,t}+\theta_3\mathbf{Control}_{i,t}+\varepsilon_{i,t} \quad \textbf{(M4)}$$

$$\mathbf{Servitization}_{i,t}=\omega_1+\omega_2\mathbf{Cdc}_{i,t}+\omega_3\mathbf{Us}_{i,t}+\omega_4\mathbf{Cdc}_{i,t}*\mathbf{US}_{i,t}+\omega_5\mathbf{Control}_{i,t}+\varepsilon_{i,t} \quad \textbf{(M5)}$$

$$\mathbf{Servitization}_{i,t}=\eta_1+\eta_2\mathbf{Cdc}_{i,t}+\eta_3\mathbf{As}_{i,t}+\eta_4\mathbf{Cdc}_{i,t}*\mathbf{AS}_{i,t}+\eta_5\mathbf{Control}_{i,t}+\varepsilon_{i,t} \quad \textbf{(M6)}$$

Model (M1) verifies the impact of strategic flexibility on the servitization of advanced manufacturing enterprises. If the coefficient α_2 is significantly positive, it indicates that strategic flexibility significantly promotes the servitization of advanced manufacturing industry; Model (M2) is based on the establishment of Model (M1) to verify that strategic flexibility can significantly affect the dynamic capabilities of advanced manufacturing enterprises; Model (M3) verifies the mediating role of enterprise dynamic capabilities between strategic flexibility and servitization. Model (M4) is designed to verify that dynamic capabilities significantly affect the level of servitization in advanced manufacturing, which is a prerequisite for conducting moderation effect tests; Model (M5) and Model (M6) validate the moderating effect of unabsorbed redundant resources and absorbed redundant resources on the relationship between dynamic capabilities and enterprise serviceability level.

4.4 Research Methodology

This article uses quantitative research methods to conduct empirical analysis on the collected data, which are all from third-party databases such as Wind and CSMAR. Finally, a total of 1230 observation data from 246 enterprises were obtained. The selection of samples is based on the concept of advanced manufacturing enterprises and the industry scope of advanced manufacturing obtained by referring to relevant literature on advanced manufacturing enterprises. The data analysis tool used is STATA 18. In the process of quantitative analysis, this article applied a fixed effects model, fixed industries and time, and conducted descriptive tests, collinearity tests, direct and indirect effect tests, and moderation effect tests on the data. Subsequently, in order to ensure the reliability of the results, this study conducted robustness tests by applying lagged explanatory variables, adding control variables, and Bootstrap tests to the data to verify the correctness of the hypotheses. Finally, in order to explore the impact of enterprise nature and geographical location on the main effect, this article conducted heterogeneity tests for further discussion.

5. Empirical Results and Analysis

5.1 Descriptive statistics and collinearity test

Table 1 presents the descriptive statistical results of each variable. Based on the mean strategic flexibility level of the sample enterprises being 3.449 and the standard deviation being 0.324, it indicates that the gap in strategic flexibility level among the selected advanced manufacturing enterprises is relatively small. The average value of the service-oriented level of the sample enterprises is 0.038, with a standard deviation of 0.021, indicating that the differences in the service-oriented level of the selected sample enterprise data are relatively small. In summary, this article can conclude that the selected enterprise data in this study, after being subjected to Winsorize truncation with a top and bottom 1%, had a relatively small impact on the main variables of this study due to outliers. Before conducting hierarchical regression, this article first performs a collinearity test to examine whether there is multicollinearity between sample variables. The results are shown in Table 2, where the VIFs of all variables are less than 3, indicating that there is no issue of multicollinearity among the variables and further regression analysis can be conducted.

Table 1. Decriptive Statistics

Variables	N	Mean	Sd	Min	Max
SF	1230	3.449	0.324	1.537	4.811
Servitization	1230	0.038	0.021	0.013	0.318
Cdc	1230	0.262	0.083	0.09	0.706
AS	1230	0.1	0.051	0.023	0.383
US	1230	1.594	1.28	0.504	9.979
Size	1230	22.76	1.19	20.51	26.36
LEV	1230	0.453	0.158	0.082	0.769
EN	1230	0.291	0.454	0	1

Table 2. Collinear Inspection

Variables	VIF	1/VIF
SF	1.03	0.9689
Cdc	1.19	0.8420
AS	1.17	0.8515
US	2.11	0.4739
Size	1.54	0.6510
LEV	2.31	0.4322
EN	1.18	0.8485
Mean	VIF	1.50

5.2 Direct effect test and mediation effect test

The direct effect test is a prerequisite for the mediation effect test, and the direct effects in the model need to be tested before each mediation effect test. Therefore, this article first examines the direct effect of strategic flexibility on the level of servitization. After inspection, the results are shown in Table 3. It can be seen from M1 that the regression coefficient α_2 between the level of servitization and strategic flexibility is 0.0105, p-value$<$0.01， the regression coefficient α_2 is positive and significant, and this indicates that strategic flexibility has a significant positive impact on the level of servitization, and hypothesis H1 has been validated. On the basis of establishing the direct effect, conduct a test of the mediating effect. Firstly, the establishment of the direct effect indicates that strategic flexibility can significantly explain changes in the level of enterprise servitization; Furthermore, it can be observed in M2 that the regression coefficient β_2 between dynamic capability and strategic flexibility is 0.0511, p-value$<$0.01, the regression coefficient β_2 is positive and significant, and this indicates that strategic flexibility can significantly explain changes in a company's dynamic capability level; Finally, controlling for the mediating variable of enterprise capability, in M3, this article can see that the coefficient γ_2 between the level of enterprise servitization and strategic flexibility is 0.0064 ($\gamma_2 \neq \alpha_2$), p-value <0.01, where the regression coefficient γ_3 between servitization and strategic flexibility is 0.08, p-value$<$0.01, the coefficient is significant and not zero. In M3, γ_2 is smaller than the coefficient α_2 in direct effects regression, indicating that dynamic capabilities play a role in transmitting and explaining strategic flexibility and enterprise serviceability level. Therefore, the test results indicate that the dynamic capabilities of enterprises play a partial mediating role between strategic flexibility and the level of advanced manufacturing enterprise servitization, and hypothesis H2 has been verified.

Table 3 The Results of Direct Effect and Intermediary Effect Analysis

Dependent Variable	Servitization	Cdc	Servitization
Independent Variable	M1	M2	M3
SF	0.0105*** (0.0024)	0.0511*** (0.0087)	0.0064*** (0.0024)
Cdc			0.0799*** (0.0085)
Size	0.0021*** (0.0007)	0.0073*** (0.0024)	0.0015** (0.0007)
LEV	0.0105** (0.0048)	0.0939*** (0.0174)	0.003 (0.0047)
EN	0.0014 (0.0016)	0.0187*** (0.0057)	-0.0001 (0.0015)
_cons	-0.0517*** (0.0168)	-0.1274** (0.0607)	-0.0415** (0.0161)
R2	0.1215	0.2459	0.195
F	13.42***	34.53***	29.21***

Note: * p<0.1, * * p<0.05, * * * p<0.01

5.3 Adjustment effect

Under the condition of verifying the existence of the mediating effect, this study further examined the moderating effect of redundant resources on the relationship between the dynamic capabilities of enterprises and the service-oriented level of advanced manufacturing enterprises. The results are shown in Table 4. To verify the moderating effect of this study, it is necessary to first verify that there is a significant relationship between the dynamic capability and service level of enterprises, that is, the regression coefficient θ_2 between the service level and dynamic capability of enterprises in M4 is 0.0829, p-value$<$0.01. Adjustment effect test can be conducted. On the basis of M4, the interaction term between unabsorbed redundant resources, enterprise dynamic capabilities, and unabsorbed redundant resources is added to obtain M5. The coefficient ω_4 of the interaction term in M5 is 0.0288 (p-value <0.01), the coefficient of the interaction term ω_4 is significant and positive, indicating that unabsorbed redundant resources positively regulate the relationship between enterprise dynamic capabilities and advanced manufacturing enterprise service levels. Hypothesis H3 holds true. Similarly, the coefficient of the interaction term η_4 between the absorbed redundant resources and the dynamic capabilities of the enterprise in M6 is -0.3134 (p-value <0.05), the coefficient of the interaction term η_4 is significant and negative, indicating that the absorbed redundant resources negatively regulate the relationship between the dynamic capabilities of the enterprise and the service-oriented level of advanced manufacturing enterprises. Hypothesis H4 holds true.

Table 4 Regulatory Effect Analysis Results

Dependent Variable	Servitization		
Independent Variable	M4	M5	M6
Cdc	0.0829*** (0.0072)	0.1017*** (0.0084)	0.0707*** (0.0072)
US		0.0063*** (0.0013)	
AS			0.113*** (0.0119)
Cdc*US		0.0288*** (0.0086)	
Cdc*AS			-0.3134** (0.126)
Size	0.0015*** (0.0006)	0.0014** (0.0006)	0.0025*** (0.0006)
LEV	0.0017 (0.004)	0.0266*** (0.0061)	0.0071* (0.0039)
EN	-0.0005 (0.0014)	-0.0005 (0.0013)	0.0002 (0.0013)
_cons	-0.0184 (0.0121)	-0.0415*** (0.0128)	-0.0525*** (0.0122)
R2	0.1916	0.2107	0.2486
F	43.65***	34,59***	46.47***

Note: * p<0.1, * * p<0.05, * * * p<0.01

6. Robustness Test

6.1 Lag explanatory variables

This article takes into account the time lag effect of corporate strategic flexibility on the level of servitization when verifying the mediating and moderating effects. The explanatory variables are lagged by one period and then subjected to regression testing. Referring to the research of Yang and Han (2024), considering that the impact of corporate strategic flexibility on service level takes a long time, a lag of one period in the explanatory variable may not be sufficient to reflect this impact[53]. In this study, the explanatory variable was regressed with a lag of two periods in the stability test. The regression results are shown in Table 5. The regression coefficients of all models are positive and significant at the 1% level, indicating that the hypothesis test still holds and the regression results are consistent with the previous test results.

Table 5. Regression Test Results of Explanatory Variable Lag Phase II Treatment

Dependent Variable	Servitization	Cdc	Servitization
Independent Variable	M1	M2	M3
L2.SF	0.0097*** (0.0026)	0.0444*** (0.1002)	0.0062*** (0.0025)
Cdc			0.0793*** (0.0092)

_cons	-0.0547*** (0.0179)	-0.1212*** (0.0693)	-0.0451*** (0.0171)
Controls (3)	Yes	Yes	Yes
R2	0.1485	0.2465	0.2287
F	11.36***	25.59***	24.86***

Note: * p<0.1, * * p<0.05, * * * p<0.01

6.2 Increase control variables

In order to reduce the impact of omitted variables on the research results, referring to Zhao and Chen's (2022) study, this study added board size (Bsize) as a control variable to the research model and conducted regression analysis again[54]. The results are shown in Table 6. After adding a new variable, the regression coefficients of M1, M2, and M3 were positive and significant, which is consistent with previous studies, assuming that H1 and H2 still hold true. The coefficient of the M5 interaction term is positive and significant, so assuming H3 holds true; The coefficient of M6 interaction term is negative and significant, so assuming H4 holds true.

Table 6. The Regression Results After Adding A Control Variable

Dependent Variable Independent Variable	Servitization	Cdc	Servitization	Servitization	Servitization	Servitization
	M1	M2	M3	M4	M5	M6
SF	0.0103*** (0.0024)	0.0517*** (0.0088)	0.0061** (0.0024)			
Cdc			0.0906*** (0.0085)	0.0838*** (0.0072)	0.1025*** (0.0084)	0.0717*** (0.0072)
US					0.0062*** (0.0013)	
Cdc*US					0.0292*** (0.0086)	
AS						0.1124*** (0.0119)
Cdc*AS						-0.3172** (0.1257)
Controls (4)	Yes	Yes	Yes	Yes	Yes	Yes
_cons	-0.041** (0.0184)	-0.1614*** (0.0665)	-0.028 (0.0176)	-0.0031 (0.0134)	-0.0272* (0.0141)	-0.038** (0.0135)
R2	0.1234	0.2471	0.1980	0.1963	0.2145	0.2527
F	11.16***	27.96***	24.99***	36.48***	30.60***	40.93***

Note: * p<0.1, * * p<0.05, * * * p<0.01

6.3 Re examination of the mediating effect

Considering the issue of weak testing power in stepwise regression, drawing on the research of Alfons et al. (2022), this paper uses Bootstrap method to further test the mediating effect of the hypothesis[55]. This article selects 5000 iterations for calculation, and the results are shown in Table 7. The confidence intervals for the indirect effects of enterprise strategic flexibility [0.00125, 0.00339] and the direct effects [0.0044, 0.0141] do not include zero, further indicating that dynamic capabilities play a partial mediating role in the relationship between enterprise strategic flexibility and advanced manufacturing enterprise servitization. Hypothesis H2 has been verified again.

Table 7. Bootstrap Verification

Outcome variable	Mediating variable	Effective stage	Effect value	Sd	95% confidence interval	
					Lower limit	Upper limit
Servitization	Cdc	Indirect effect	0.0023	0.0006	0.00125	0.00339
		Direct effect	0.0093	0.0025	0.0044	0.0141

7. Heterogeneity Test

7.1 Nature of Enterprise

China implements a socialist market economy, under which state-owned and non-state-owned enterprises coexist, forming a situation with Chinese characteristics in the economy. State owned enterprises dominate many important fields and strategic industries, while non-state-owned enterprises provide competition in other fields and promote market vitality, so this study categorizes the nature of enterprises into state-owned enterprises and non-state-owned enterprises. In this discussion, there were 71 state-owned enterprises and 175 non-state-owned enterprises. State owned enterprises and non-state-owned enterprises have different business objectives and models, so their grasp and response to strategies are also different, resulting in different impacts on servitization. On the one hand, state-owned enterprises have close ties with the government and can directly receive policy guidance and resource support. At the same time, state-owned enterprises are often able to implement government macroeconomic control measures more quickly in strategic decision-making, thereby improving their response speed. This structure enables them to quickly adjust their strategies in the face of market changes. Therefore, state-owned enterprises have a higher level of strategic flexibility and a greater impact on servitization. On the other hand, non-state-owned enterprises often lack close ties with the government and have fewer channels to obtain policy information. Moreover, non-state-owned enterprises require more time for internal coordination and market evaluation in the decision-making process, resulting in a slower response speed. This relative independence makes non-state-owned enterprises appear more cautious in responding to market changes, therefore their strategic flexibility level is lower compared to state-owned enterprises, and their impact on servitization is not as significant as state-owned enterprises.

In order to examine the impact of enterprise nature on strategic flexibility and advanced manufacturing enterprise service-oriented level, this paper divides enterprises into two groups based on their nature: state-owned enterprises and non-state-owned enterprises, and conducts group regression analysis [56]. The heterogeneity test results of enterprise nature are shown in Table 8. In column (1) of state-owned enterprises, the regression coefficient of enterprise strategic flexibility is 0.01943, which is significant at the 1% level. However, in column (2) of non-state-owned enterprises, the regression coefficient of enterprise strategic flexibility is 0.0055, which is only significant at the 10% level. Through the heterogeneity test of enterprise nature, it can be found that under different conditions of enterprise nature, the positive impact of enterprise strategic flexibility on the servitization of advanced manufacturing enterprises varies. Although both coefficients are positive, in terms of coefficient size and significance level, strategic flexibility can more effectively promote the improvement of service level in state-owned advanced manufacturing enterprises.

7.2 Geographic location

Considering the differences in economic development levels and stages, the impact of corporate strategic flexibility on the servitization of advanced manufacturing enterprises will exhibit significant heterogeneity at the regional level. On the one hand, enterprises located in the east have developed economies and fierce market competition, and must quickly adapt to changes to maintain competitiveness. Moreover, the information flow in the eastern region is smoother, policy guidance is obtained more timely, and technology and talent resources are abundant. These factors enable eastern enterprises to effectively support strategic changes to adapt to environmental changes. Therefore, advanced manufacturing enterprises located in eastern China have higher strategic flexibility and have a more effective impact on servitization. On the other hand, enterprises located in the central and western regions have weak economic foundations, poor information flow, talent shortages, and stable market environments. This makes them have lower strategic flexibility compared to economically developed advanced manufacturing enterprises in the eastern region, and their impact on service orientation is not as significant as that of eastern enterprises.

Referring to Liu et al.'s (2024) research on heterogeneity testing, this study divided advanced manufacturing enterprises into three groups based on geographical location: eastern, central, and western, and then conducted regression analysis on each group[56]. The results of the heterogeneity test on geographical location are shown in Table 8. In column (3) of the advanced manufacturing enterprises in the eastern region, the regression coefficient of strategic flexibility is 0.0059, which is significant at the 5% level; In column (4) of advanced manufacturing enterprises in the central region, the regression coefficient of enterprise strategic flexibility is 0.0034, which is not significant; In column (5) of advanced manufacturing enterprises in the western region, the regression coefficient of strategic flexibility is 0.0213, which is not significant. Although the coefficients of all three are positive, strategic flexibility can more effectively affect the level of enterprise serviceability in advanced manufacturing enterprises in the east, which is consistent with the research conducted above.

Table 8. Heterogeneity test of enterprise nature and regions

Dependent Variable Independent Variable	Servitization				
	(1)	(2)	(3)	(4)	(5)
SF	0.0194***	0.0055*	0.0059**	0.0034	0.0213
	(0.0045)	(0.0028)	(0.0026)	(0.0057)	(0.0128)
Controls	Yes	Yes	Yes	Yes	Yes
_cons	-0.1524***	-0.0111	-0.0128	0.0343	-0.3022***
	(0.0336)	(0.0193)	(0.0175)	(0.046)	(0.0649)
R^2	0.2355	0.0997	0.1370	0.1599	0.5173

Note: * p<0.1, * * p<0.05, * * * p<0.01

8. Conclusion and Discussion

This study used fixed effects regression analysis to explore the causal relationship and mechanism between corporate strategic flexibility and servitization. By analyzing data from 246 Chinese A-share listed companies from 2018 to 2022, suggestions for the path of service-oriented manufacturing were proposed and empirically tested. Research has found that the servitization of manufacturing can be achieved by enhancing the strategic flexibility of enterprises, and dynamic capabilities play a mediating role in the process of promoting servitization through strategic flexibility. In addition, dynamic capabilities are positively regulated by unabsorbed redundant resources and negatively regulated by absorbed redundant resources in promoting enterprise servitization. This study helps to provide an exploration path and future development direction for the implementation of service-oriented manufacturing, as well as filling the research gap in the current academic community on how to achieve service-oriented issues.

Based on the H1 and H2 hypotheses, this study provides direction for manufacturing enterprises on how to achieve servitization. Firstly, manufacturing enterprises need to flexibly change their corporate strategies based on internal and external environments, in order to promote the transformation process towards service-oriented enterprises. Secondly, in this process, developing the dynamic capabilities of the enterprise, constantly coordinating internal and external resources to adapt to changes in the environment, thereby enhancing its competitiveness. This study assumes that H3 and H4 are valid, and that dynamic capabilities can regulate resources to promote their own development. Unabsorbed redundant resources can be applied to other areas of the enterprise, thereby reducing the loss of unnecessary products and promoting the sustainability of the enterprise. Therefore, manufacturing enterprises can also accelerate the process of transitioning to service-oriented by increasing their own unabsorbed redundant resources.

9. Limitations and Future Research

This study provides empirical findings on the successful servitization of manufacturing industry. However, this study has some limitations and provides direction for future research. Firstly, the sample used in this study is advanced manufacturing enterprises in China. Considering the differences in economic development levels between emerging economies and developed countries, the distinct economic characteristics of different countries, and the differences in manufacturing and advanced manufacturing industries, the universality of the results of this study may still need to be improved. In future research, more empirical evidence can be used to enhance the universality of the study. Manufacturing enterprise managers should adopt a cautious attitude when drawing on the results of this study. Secondly, servitization involves complex processes, and the measurement of servitization should be more refined, rather than solely based on service related revenue and the proportion of service personnel. Thirdly, this study explores the impact path of strategic flexibility on servitization from the perspective of dynamic capabilities. Due to the complexity of servitization and strategic flexibility themselves, there are also multiple paths of influence between them. This article only uses dynamic capability as a mediating variable between the two. In future research, organizational learning and other factors can also be added to the model to explore the implementation path of manufacturing servitization, making the research results more comprehensive. Finally, considering that this study used second-hand data for empirical analysis, a questionnaire survey method can be used in future research to verify the results and make them more accurate and convincing.

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Measurement of Digital Transformation Level of Iron and Steel Enterprises: Based on Data from Listed Companies in China's Iron and Steel Industry

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Abstract. In the epoch of digital economy, the integration and development of digital technology and traditional industries has accelerated the digital transformation of iron and steel enterprises. Constructing a digital transformation index system for iron and steel enterprises can effectively assess the transformation process and accelerate the high-quality growth of digital economy. This paper constructs a digital transformation level measurement and evaluation index system for iron and steel enterprises, with the elements of their digital transformation mechanism serving as the fundamental framework. The financial data of 26 listed enterprises in China's steel sector are used as research samples, and the digital transformation level is measured by the Entropy weight -Topsis method. The results show that the comprehensive level of digital transformation of Chinese iron and steel firms is not high and the transformation speed is relatively slow. For this reason, we propose the following suggestions to speed up the digital transformation and upgrading of iron and steel enterprises from the aspects of increasing government policy guidance and capital investment, strengthening the construction of enterprise digital transformation infrastructure, and improving the talent training system for digital transformation.

Keywords. Digital transformation; Iron and steel enterprises; Evaluation index system

1. Introduction

A new round of shift from traditional manufacturing to intelligent manufacturing modes has been promoted by the deep convergence of new-generation information technology with traditional manufacturing industries. Digitization, intelligence and virtualization technologies penetrate through the entire production process and the entire life-cycle of products. Although enterprises are acquainted with the necessity and importance of digital transformation[1], it is rare for them to develop a complete and systematic digital blueprint. In the progress of digital transformation, firms are faced with many problems. Those includes "reluctant to turn" due to solidified consciousness, "unable to turn" due to weak digital technology, and "afraid to turn" due to large transformation risks[1].

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According to relevant statistics, only about 25% Chinese enterprises carry out digital transformation, much lower than 54% in the United States and 46% in Europe.

In recent years, digital technology, digital platform and intelligent manufacturing technology have been extensively employed in the digital transformation process of iron and steel firms. At present, over 80% of domestic iron and steel firms in China have been continuously advancing intelligent manufacturing. Moreover, leading backbone enterprises of steel industry have basically completed the four-level system of the top-down vertical integration. Basic automation, PCS (process control system), MES (production execution system) and manufacturing management system at the production line level have been made. According to the relevant data, there is over 10 billion yuan of special investment for the digital transformation and retrofitting of steel firms throughout 2021. However, the current digital transformation of steel firms is facing many internal and external factors[2]. High quality digital transformation is difficult, and the quality evaluation of transformation has not formed a standard system. Transformation process in the enterprises is without a good reference standard, thus the pace of their transformation slowing down.

Therefore, we construct a digital transformation evaluation index system by analyzing the digital transformation mechanism of iron and steel enterprises. Attention is directed toward the digital transformation level exhibited by Chinese iron and steel enterprises. Finally, we propose policy recommendations to enhance the digital transformation of China's steel firms.

Considering the existing literature and prior researches, this paper makes significant contributions in the following aspects:

(1) Analyzing the ecological mechanism of digital transformation of steel firms from four aspects: policy and system construction, digitization of the entire product life cycle process, digital products enrichment and flattening of enterprise organization structure.
(2) Compared with the lack of existing indicators, this paper constructs a digital transformation indicator evaluation system taking four dimensions into account: production process intelligence, organizational restructuring, service model innovation and policy and system construction.
(3) The data of listed iron and steel enterprises in China are selected. The digital transformation level of firms is measured on the basis of the Entropy weight-Topsis method, and countermeasure suggestions for accelerating digital transformation are formulated in terms of the evaluation results.

2. The digital transformation evaluation index system for iron and steel enterprises

Via three stages of literature combing, brainstorming and field interviews, 8 primary indicators and 16 secondary indicators are proposed based on 4 dimensions of production process intelligence, organizational structure reorganization, service model innovation and policy and system construction. The details are shown in Table 1.

(1) Intelligent production process: It includes two first-level indicators : digitalization of R&D process and digitalization of production process[3]. For steel companies, their production process involves the R&D and manufacturing process of the whole product cycle. The degree of digitization of the R&D and production process is reflected in the amount of digital input and the level of

digitization of the R&D technology; Secondly, digital system integration and interaction can also improve business productivity and increase economic benefits for companies. The increase in digital business output also reflects the positive utility of digital transformation.

(2) Organizational structure restructuring[4]: Digital transformation of enterprises is never just a reorganization of products and business models. In the transformation process, flat and decentralized organizational restructuring helps business response agilely and quickly; The level of quality of digital personnel and talent pool are the key factors to improve the organizational adaptability of traditional steel companies and enhance the digital transformation of enterprises.

(3) Service model innovation: On one side, the government should guide the digital transformation of industry by playing the synergistic effect of industrial clusters, encourage industry leading enterprises and platform enterprises to open technology, platform and data resources to upstream and downstream enterprises, and build industrial Internet platforms. Thus, the level of industrial digitalization will be promoted in a concerted manner. On the other side, the big data service platform should be leveraged to improve the level of user data application, data management and information sharing and delivery[5]

(4) Policy and system construction: The government has laid great emphasis on the development of digital transformation[6]. Policy measures for the steel sector have been launched through systematical implementation, with the establishment of enhanced organizational frameworks to achieve policy synergies. In addition, from the perspective of business operation management, the production management system and digital information management system also have a significant impact on the level of digitization. Meanwhile they need to ensure a tight connection between staff and equipment to achieve integration of structural information.

Table 1. Evaluation index system of digital transformation of steel enterprises

Index Dimension	Primary Index	Secondary Index
Production process intelligence	R&D process digitization (B1)	Digital investment level (C11)
		R&D technology digitization level (C12)
		The ratio of digital business output value to total output value (C13)
	Digitalization of production process (B2)	Digital system integration and interaction level(C21)
		Digital information utilization level (C22)
		Level of production process intelligence (C23)
Organizational restructuring	Flat organizational structure (B3)	Level of organizational structure flattening (C31)
	Organizational management level (B4)	Digital personnel quality level (C41)
		Digital talent reserve level (C42)
Service model innovation	Collaborative innovation development (B5)	Level of collaborative innovation with industry chain enterprises (C51)
	Big data service platform (B6)	User data application level (C61)
		Data management level (C62)

		Information sharing and transmission level (C63)
Policy and system construction	Government policies for enterprises (B7)	Degree of implementation of government policies for enterprises (C71)
	Enterprise digital system construction（B8）	Enterprise digital strategy layout level（C81）
		Enterprise digital management system effectiveness（C82）

3. Digital transformation level measurement based on the Entropy Weight-Topsis Method

3.1. Sample selection and data sources

First paragraph This paper takes 26 listed steel firms as samples. The data primarily derives from the CSMAR database and Juchao.com. The data such as the annual reports of the 26 listed steel firms are extracted and sorted out yielding the necessary data for the research. Based on the availability of data, this paper selects panel data of listed companies in the steel industry to analyze the level of digital development, and initially screens 44 listed steel companies. The completeness of the data and the absence of words such as "digital", "intelligent" and "big data" in the annual reports of steel companies were considered. Therefore, 26 listed steel companies were finally determined as the study sample. The time period of the data is from 2015, when China released "Made in China 2025", marking the beginning of the fourth industrial revolution based on digital technology, to 2020.Therefore, the final time limit for data selection is 2015-2020.

3.2. Calculation of index weights based on the Entropy weight-Topsis method

The entropy weight TOPSIS method is an overall evaluation approach which combines the entropy weight method and the TOPSIS method. An objective weight is assigned to each object based on the entropy weight method, and the TOPSIS method is employed to select the optimal solution by taking into account the distance between every scheme and the ideal solution, rendering the evaluation process and results more reasonable and scientific[7].The Entropy weight- Topsis method can assess the realistic level of development of the solution to be selected or the research object by calculating the Euclidean distance between the solution to be selected and the ideal solution. This method requires less data for the survey sample. The measurement can reflect the advantages and disadvantages of each solution and its ranking, so it is widely used in many solution selection and ranking problems.

(1) Standardization of sample data.

It is assumed that the digital transformation level measurement system consists of a set of p measured objects and a set of q measured indicators. Thus, a data matrix of indicators is formed. The data is standardized by dividing the statistical value of each indicator of each sample enterprise by the mean value of the corresponding indicators of all enterprises (equation (1)). The standardized matrix A is obtained.

$$x_i(k) = x_i(k) / \frac{1}{p}\sum_{i=1}^{p} x_i(k)\left(k = 1, 2, \ldots, q\right) \tag{1}$$

$$A=\left(X_1,X_2,...,X_p\right)=\begin{bmatrix} x_1(1) & x_1(2) & x_1(3) & ... & x_1(q) \\ x_2(1) & x_2(2) & x_2(3) & ... & x_2(q) \\ ... & ... & ... & ? & ... \\ x_p(1) & x_p(2) & x_p(3) & ... & x_p(q) \end{bmatrix} \tag{2}$$

In formula X_i is the i-th sample data and $X_i=(x_i(1),x_i(2),\cdots,\ x_i(q))(i=1,2,\cdots,p)$

(2) Standardized matrix entropy weighting. Firstly, we calculate the entropy weight of each index, and then calculate the index weight $B_i(k)$, index entropy value $e(k)$ and index variability coefficient $g(k)$ for the standardized data. Finally, we obtained the weights of each indicator $W(k)$.

$$B_i(k)=x_i(k)/\sum_1^p x_i(k) \tag{3}$$

$$e(k)=\frac{1}{\ln p}\sum_1^p B_i(k)\ln B_i(\mathrm{k}),0\le e(k)\le 1 \tag{4}$$

$$g(k)=1-e(k),0\le g(k)\le 1 \tag{5}$$

$$W(k)=g(k)/\sum_{i=1}^p g(k),0\le w(k)\le 1,w(1)+w(2)+...+w(q)=1 \tag{6}$$

Then, the set of matrix weights C after the normalization process is calculated.

$$C=A\times W \tag{7}$$

(3) The paper determines the positive and negative ideal solutions, based on relative closeness of Euclidean distance.
Positive ideal solution:

$$\mathrm{X_0}^+=\left(\mathrm{x_0}^+(1),\ \mathrm{x_0}^+(2),\ ...,\mathrm{x_0}^+(k),\ ...\mathrm{x_0}^+(n)\right),(k=1,2,...,q) \tag{8}$$

Negative ideal solution：

$$\mathrm{X_0}^-=\left(\mathrm{x_0}^-(1),\ \mathrm{x_0}^-(2),\ ...,\mathrm{x_0}^-(k),\ ...\mathrm{x_0}^-(n)\right),(k=1,2,...,q) \tag{9}$$

Then, from the set of weights B of the normalized matrix, we calculated the distance from the steel and digitally transformed state to the positive and negative ideal solution D_i^+,D_i^-:

$$D_i^+ = \sqrt{\sum_{k=1}^{q}\left[x_i(k) - x_0^+(k)\right]^2} \tag{10}$$

$$D_i^- = \sqrt{\sum_{k=1}^{q}\left[x_i(k) - x_0^-(k)\right]^2} \tag{11}$$

Finally, the relative closeness of the Euclidean distance is calculated.

$$D_i^* = D_i^- / D_i^+ + D_i^{*+} \tag{12}$$

According to the Entroty weight- Topsis method, we can evaluate the index weights of the digital transformation for iron and steel enterprises, which is shown in Table 2.

Then, from the set of weights B of the normalized matrix, we calculated the distance from the steel and digitally transformed state to the positive and negative ideal solution :

Finally, the relative closeness of the Euclidean distance is calculated.

According to the Entroty weight- Topsis method, we can evaluate the index weights of the digital transformation for iron and steel enterprises, which is shown in Table 2.

Table 2. Evaluation index weights of digital transformation for steel companies.

Primary indicators	Weight	Secondary indicators	Weight
Digitalization of R&D process (B1)	0.1501	Digital investment level (C11)	0.0672
		Digitalization level of R&D technology (C12)	0.0829
		Proportion of digital business output value to total output value (C13)	0.0491
Digitization of production processes (B2)	0.3463	Level of digital system integration and interaction (C21)	0.0921
		Level of digital information utilization (C22)	0.0688
		Level of production process intelligence (C23)	0.1854
Flat organizational structure (B3)	0.0832	Level of organizational structure flattening (C31)	0.0832
Organizational management level (B4)	0.1128	Level of digital personnel quality (C41)	0.0451

		Level of digital talent reserve (C42)	0.0677
Collaborative innovation development (B5)	0.0732	Level of collaborative innovation with industry chain enterprises (C51)	0.0732
Big data service platform (B6)	0.1439	Level of user data application (C61)	0.0541
		Data management level (C62)	0.0471
		Information sharing and delivery level (C63)	0.0427
Government policies for enterprises (B7)	0.1243	Degree of implementation of government policies for enterprises (C71)	0.1243
Enterprise digital system construction (B8)	0.0781	Level of enterprise digital strategy layout (C81)	0.0385
		Effectiveness of enterprise digital management system (C82)	0.0451

3.3. Evaluation results of digital transformation level of steel enterprises

We employed Matlab to measure and analyze the level of digital transformation of China's steel companies with data from 26 listed steel companies. The Entropy weight-Topsis method was used to quantify the level of digitization under each index of the steel company. The results are shown in Table 3. From the measurement results, except for three indicators of digital investment level, digital information utilization level and the data management level, the measured value is over 10%. The rest of the indicators of digitalization level are below 10%. It shows that the overall level of digital transformation of China's steel firms is not high. The speed of digital transformation needs to be further accelerated.

Table 3. Digitized level values of various measurement indexes of Chinese iron and steel enterprises

Measure indicators	Measure value	Measure indicators	Measure value
Digital investment level	12.77	digital talent reserve level	7.19
R&D technology digitalization level	9.61	Level of collaborative innovation with industry chain enterprises	3.18
The ratio of digital business output value to total output value	6.34	User data application level	7.53

Digital system integration and interaction level	8.75	Data management level	12.26
Digital information utilization level	13.74	Information sharing and transmission level	5.42
Level of production process intelligence	9.20	Degree of implementation of government policies for enterprises	8.94
Level of organizational structure flattening	7.32	Enterprise digital strategy layout level	7.45
Digital personnel quality level	5.62	Enterprise digital management system effectiveness	6.47

4. Main conclusions and suggestions

Based on clarifying the mechanism elements of digital transformation of iron and steel enterprises, this paper draws the theoretical model of digital transformation ecosystem of steel firms. The digital transformation level measurement index system is constructed. And the Entropy weight-Topsis method serves to measure the level of digital transformation. The results show that the overall level of digital transformation of iron and Steel entities show room for improvement and the transformation speed is slow. For this reason, the following suggestions are put forward.

(1) We propose that the government should strengthen the policy guidance and support for the digital transformation of steel firms. The introduction of policies has provided policy dividends for the digital transformation of steel companies. However, whether these systems and policies can be implemented requires guidance and supervision by government departments at all levels. At the same time, governments at all levels should give appropriate financial subsidies during the digital transformation of firms, or enhance digital inclusive financial services to reduce the threshold of enterprise financing.

(2) Strengthening the digital infrastructure of steel enterprises. Enterprises should first lay a robust foundation for digital transformation to realize digital transformation. And they should build a solid digital transformation platform and increase the investment in digital transformation infrastructure. Manufacturing enterprises should focus on 5G, big data, blockchain, cloud computing, industrial Internet of Things, AI (artificial intelligence), and other areas to build digital transformation infrastructure platform. And with the support of digitalization and intelligent technology, the traditional infrastructure should be upgraded and transformed.5G network base station, big data research center, intelligent production line, digital twin workshop, data sharing open platform, user personalized experience center, etc., including digital production, management, sales as one of the infrastructure and platform needs to be built.In

this way, the digital transformation foundation of manufacturing enterprises is guaranteed.

(3) This paper suggests to improve the digital transformation talent training system of steel companies. The construction of digital transformation talent team is an essential cornerstone for enterprises to quickly realize digital transformation. Enterprises should continuously attract excellent talents and adopt advanced technologies to achieve total factor productivity. While increasing the proportion of labor cost expenditure, enterprises should pay more attention to learning ability besides academic level, and train more digital-related talents by conducting skills training.

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Part II

Interdisciplinary Field of Modern Management and Big Data

Modern Management based on Big Data VI
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An AI-Powered Instructional Design and Evaluation Framework Based on POA and ChatGPT

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Abstract. To bridge the gap between Artificial Intelligence (AI) potential and pedagogical implementation, this study constructs a generative AI education model based on ChatGPT to address superficial AI integration in pedagogic education. Employing a mixed method research (MMR) approach, it formulated a framework for integrating ChatGPT or DeepSeek to enhance Production-Oriented Approach (POA) teaching design from 6 key phases of the POA model and subsequently developed a generative AI evaluation system model. We conducted empirical validation across 10 English education major classes. The findings indicate that the generative AI evaluation system facilitates high-precision dynamic assessments of teaching capabilities. AI technology enhances teaching design precision and efficiency through dynamic diagnostics and real-time feedback. More crucially, it catalyzes a paradigm shift in teacher education by establishing data-driven feedback loops that enable adaptive evolution of pedagogical practices.

Keywords. ChatGPT, AI, Generative Education

1. Introduction

The contemporary era is characterized by a significant transition from industrial civilization to digital civilization. The rapid advancement of intelligent technology clusters, including GPT, big data, and cloud computing, is driving profound structural transformations within the educational landscape[1]. The World Economic Forum's *Future of Jobs Report 2023* highlights that artificial intelligence and automation technologies are projected to reshape nearly half of global corporate work tasks by 2027, consequently, the education sector, as a critical domain for technological application, is poised to undergo a fundamental restructuring of its teaching processes and knowledge dissemination models[2].

The advanced semantic understanding, multi-modal interaction, and knowledge generation capabilities of generative AI offer crucial technical support for the

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development of personalized, contextualized, and intelligent teaching systems[3]. Simultaneously, these advancements also present a paradigm shift in the talent training models of traditional pedagogical education.

However, a trend of superficial technological application persists within pedagogical education, where artificial intelligence has yet to be deeply integrated. This limitation primarily manifests in the predominant focus of AI education research on validating the performance of isolated tools (e.g., grammar correction accuracy and functional metrics of automated scoring systems), while neglecting systematic investigation into their practical implementation within authentic educational settings and lacking a structured framework covering the entire instructional cycle of 'design, implementation, and evaluation'. This disparity represents a significant impediment to the digital transformation of education, particularly in light of the disruptive changes induced by generative AI[4]. In order to break through this problem, our study proposed an AI-powered instructional design and evaluation framework based on POA and ChatGPT.

2. Research Status

Compared to other artificial intelligence technologies, ChatGPT offers unprecedented opportunities in personal learning, instant feedback, resource efficiency, accessibility, and inclusivity[5]. As a prominent representative of generative AI, ChatGPT's powerful natural language processing and content generation capabilities provide new technical support for educational informatization. By integrating advanced technologies like ChatGPT, educational informatization can further achieve technological innovation in pedagogical methods, the informationalization of educational dissemination, and the modernization of teaching approaches.

In recent years, the application of large language models such as ChatGPT or DeepSeek in generative AI education, particularly in language learning and personalized instruction[6], has become a hot topic in academic circles both domestically and internationally. A parallel intelligent education framework based on ChatGPT has been proposed, focusing on its potential as a generative AI educational tool and its supplementary role in classroom teaching[7]. The study demonstrated that effective integration of parallel intelligent education can significantly improve students' learning outcomes and comprehension abilities. The core team of Khan Academy has collaborated with OpenAI to develop *Khanmigo*, a comprehensive educational platform. As an AI tutor based on GPT-4, it supports interactive teaching in subjects such as mathematics, science, and programming, providing step-by-step problem-solving guidance, knowledge point explanations, and personalized learning recommendations[8].

3. The Process of POA Teaching Design Empowered by ChatGPT or DeepSeek

The ultimate goal of the GPT- or DeepSeek-empowered Production-Oriented Approach (POA) teaching design model explored in this study is to construct an adaptive educational ecosystem. When pre-service teachers design lesson plans based on POA theory using the model, their feedback optimizes the model's subject teaching knowledge. In turn, the model generates simulated classroom scenarios to enhance practical abilities, forming a "Möbius strip-like evolutionary cycle" evolution in the field of education. The process of POA teaching design empowered by ChatGPT or DeepSeek is illustrated in **Figure 1**.

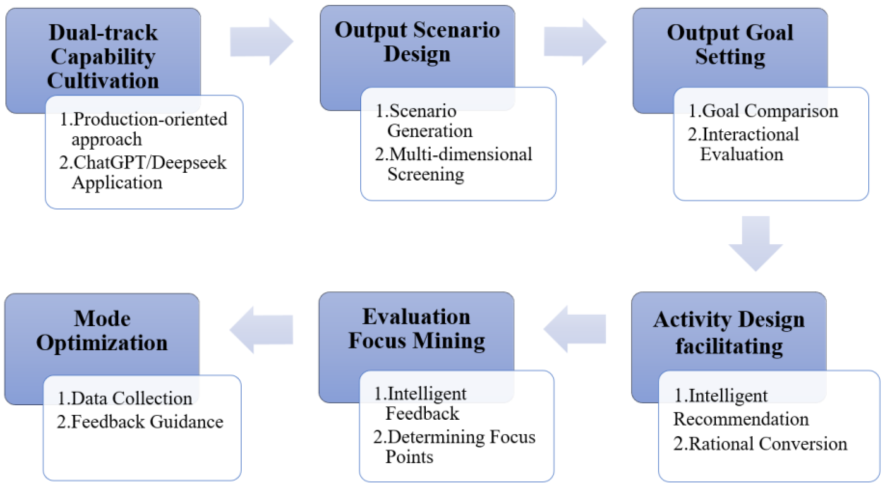

Figure 1. The POA instructional design process enabled by ChatGPT and DeepSeek

3.1. Phase 1: Dual-Track Capability Cultivation

The capacity-building process initiates with parallel training modules: (a) theoretical grounding in POA principles, emphasizing output scenario formulation and activity chain orchestration. (b) applied training on intelligent tools (ChatGPT/DeepSeek), addressing functional limitations, prompt engineering techniques, and content filtration protocols. Through case deconstruction, simulated implementation, and real-time feedback, this phase systematically reinforces human-AI collaboration awareness.

3.2. Phase 2: Output Scenario Design

Building upon thematic requirements, learners engineer task scenarios by inputting structured prompts into AI tools. Post-generation, a multi-criteria evaluation matrix is applied under instructor guidance, assessing:

- Topic alignment and difficulty calibration
- Authenticity of situational roles/contexts
- Pedagogical effectiveness in language acquisition
- Interactive element optimization

This structured selection ensures scenario viability while embedding engagement drivers to stimulate learner participation.

3.3. Phase 3: Output Goal Setting

Learners compare examples with expected teaching objectives, analyzing language difficulty, content completeness, and structural logic. Subsequently, learners exchange initial output works and use ChatGPT or DeepSeek for evaluation, requiring them to summarize common issues in aspects below:

- Depth of viewpoint expression
- Language accuracy and fluency
- Rationality of article structure

Then, learners have ChatGPT or DeepSeek extract content, language, and structural information closely related to the theme from the thematic material library and student works, and summarize the teaching key points. After integrating the results of intelligent analysis with their own teaching experience, learners should select teaching key points based on the teachability principle of output goals, and supplement considerations of learners' practical application and cognitive characteristics in the campus environment and current international situation to determine the final teaching objectives.

3.4. Phase 4: Activity Design Facilitating

Learners prompt ChatGPT or DeepSeek to generate a vocabulary list and interactive activity suggestions related to the topic, with detailed classifications. Using this as a reference, learners brainstorm within their groups to supplement vocabulary, then designing diverse classroom exercises. Next, they ask ChatGPT or DeepSeek to extract relevant cases from the thematic material library and transform them into tasks or questions suitable for classroom practice. Combining these tasks and questions, they should design classroom teaching activities, reasonably arrange the activity sequence, ensuring a progression from simple to complex, from single-skill training to comprehensive ability enhancement, thereby constructing a coherent and effective activity facilitation chain.

3.5. Phase 5: Evaluation Focus Mining

After learners complete the initial draft of the course introduction design, they need to instruct ChatGPT or DeepSeek to analyze the shortcomings of the initial draft. After receiving feedback from ChatGPT or DeepSeek, learners exchange their works, quickly review and verify the issues pointed out by ChatGPT or DeepSeek. And, in conjunction with teaching objectives and their own actual level, learners determine the evaluation focus based on the principles of typicality, teachability, gradualness, and systematicness of the evaluation focus.

3.6. Phase 6: Mode Optimization

Following the collection of multidimensional student data throughout the entire teaching process (classroom performance, task completion, and self-assessment/peer-assessment data), statistical methods are employed for data analysis. Based on data-driven feedback, the strengths and weaknesses of learners in utilizing ChatGPT or DeepSeek for POA instructional design are summarized.

Subsequently, teachers guide learners in establishing instruction optimization mechanisms to address the randomness in ChatGPT responses. For issues related to the preliminary design and suggestions from ChatGPT or DeepSeek, learners are guided to formulate systematic content deepening strategies. Learners must address three critical aspects during AI-assisted material development:

- Theoretical-practical alignment
- Contextual knowledge supplementation
- Cultural relevance calibration

4. Technical Framework Design of the Generative AI Evaluation System Model

Building upon the aforementioned practice path of POA teaching design empowered by Generative AI, this research aims to overcome the triple challenges of "data discretization," "subjectivity in evaluation," and "inefficiency in iteration" in human-computer collaboration. We translated the dynamic interaction at the process level into a systematic mapping at the technical level. And it is achieved by constructing a multi-modal data foundation to capture the behavioral trajectories throughout the entire teaching cycle and leveraging machine learning algorithms to achieve quantitative analysis of POA elements. This Generative AI evaluation system model focuses on cultivating the teaching abilities of normal learners. It adopts the "Production-Oriented Approach" as its theoretical framework and integrates Generative AI technology to construct a cross-disciplinary dynamic evaluation system. It forms a path of "practice demand-driven technology development - intelligent diagnosis feeding back into ability evolution," exploring the common development mechanism of normal learners' subject teaching abilities under the human-computer collaboration model. The technical framework and operational process of the POA teaching design Generative AI evaluation system model are illustrated in **Figure 2**.

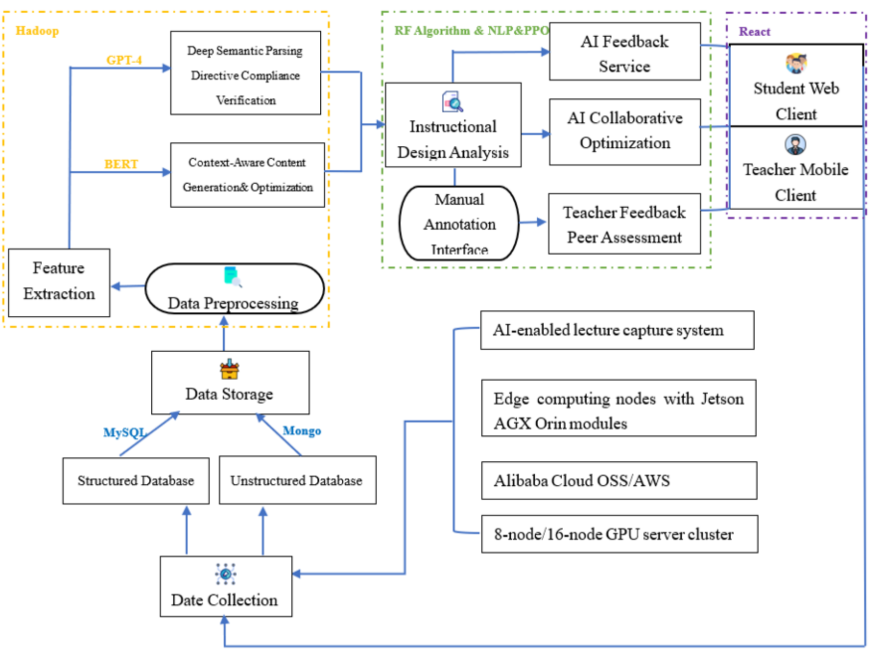

Figure 2. Technical framework of generative AI teaching design evaluation system

Establishing a multimodal data foundation is the most fundamental step. Data that includes voice, text, behavior, and subjective evaluation from classroom teaching should be integrated to construct a structured database. A voice feature library records acoustic parameters such as speech rate and intonation. A teaching design quality library stores evaluation indicators like target matching degree and activity logic, and an AI interaction archive tracking technical application data such as instruction optimization and generated content utilization, providing comprehensive data support for intelligent analysis.

The second step is developing core analysis algorithms. We constructed a machine learning-based teaching design quality evaluation model by inputting POA-driven features (e.g., target adaptability, activity complexity) and generating quantitative scores through a random forest algorithm trained on 137 annotated high-quality multimodal teaching cases (voice, text, behavioral logs). The model dynamically optimized feature weights by incorporating the teachability principles from POA theory. For AI tool adaptability, we developed BERT-based semantic similarity detectors and content filtering algorithms to ensure educational alignment in human-computer interaction (HCI).

Third, to build an intelligent diagnostic system is a crucial process. We focus on constructing a dynamic evaluation matrix containing 12 secondary indicators, with teaching design ability (60%), AI tool application (30%), and teaching reflection ability (10%) forming a three-level evaluation system. Then we should develop a real-time feedback engine to automatically generate diagnostic reports through natural language processing, which highlights high-priority issues such as "target difference deviation > 0.5," and visualizes the distribution of group capabilities using heatmaps.

The fourth step is to construct a human-computer collaborative optimization mechanism, designing a three-channel (teacher, intelligent system, learning partners) feedback system. The combination of these three forms a "trial teaching-diagnosis-improvement" closed-loop training system, with each iteration generating a capability growth curve and improvement path map.

Fifth, we need to conduct system verification and optimization. The system adopts dual-expert validation: theoretical verification by education specialists and technical code audits by engineers. This process quantifies efficacy differences between traditional and AI-enhanced training for standard learners. The system features a dynamic parameter adjustment mechanism: algorithms automatically optimize the weights of evaluation metrics using validation data, while preserving educator-configurable interfaces to ensure flexible pedagogical customization.

Finally, a layered application architecture should be deployed. This process includes front-end development for a teacher management interface and a student training platform, alongside a back-end designed as a distributed system to support concurrent multi-user access. Also, this system is complemented by a continuous evolution mechanism, featuring a monthly updated POA case library and a quarterly upgraded NLP engine. Throughout implementation, robust educational ethics protection is paramount. Differential privacy techniques are employed for sensitive data handling, and an emergency manual evaluation channel is established to ensure a deep alignment between technological empowerment and educational principles.

5. Conclusion

This study, through the construction of a Generative AI-enabled POA teaching design process and its supporting evaluation system, empirically reveals the significant enhancement effect of the human-AI collaboration model on the cultivation of pre-service teachers' teaching abilities. Experimental results demonstrate that AI technology not only optimizes the accuracy and iterative efficiency of teaching design through dynamic diagnosis and real-time feedback but also reconstructs the practical paradigm of traditional pedagogical education with a "data-driven-ability-feedback" evolutionary mechanism.

However, the research still has limitations. First, the experimental samples are concentrated in the English subject, and the cross-disciplinary generalization ability requires further verification. Future studies should validate the framework in STEM and humanities by adapting AI training datasets to incorporate domain-specific pedagogical knowledge. Second, the risk of teachers and students' technical dependence on AI tools needs long-term tracking and evaluation. To mitigate over-reliance, a human-AI collaborative decision-making mechanism should be established, including setting AI suggestion thresholds and designing teacher creativity-weighted algorithms.

Ethically, we implemented differential privacy by adding calibrated noise to sensitive data (e.g., student interaction logs) and restricting query frequency, ensuring individual anonymity without compromising analytical utility.

Future research will expand multi-disciplinary application scenarios, develop more adaptive meta-evaluation algorithms, and deepen the research on the boundaries of human-machine rights and responsibilities in the ethical dimension to promote the two-way empowerment of intelligent technology and educational laws.

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Modern Management based on Big Data VI
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Enhanced Text-to-SQL Generation via Query Classification

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Abstract. With the popularization of big data technologies, the demand for non-technical personnel to directly manipulate databases through natural language is growing. However, existing text-to-SQL methods still suffer from insufficient accuracy and efficiency when dealing with multi-table complex queries, especially on large-scale cross-domain datasets. This paper proposes a text-to-SQL method that integrates query classification, query intermediate representation and dynamic example selection. The method links natural language entities to database structures through a schema linking module, designs a query classification module to distinguish between simple and complex queries, and provides corresponding hint templates for different categories of queries. For multi-table complex queries, which often suffer from connection errors, the method introduces query intermediate representation and a dynamic example strategy to address these issues. Experiments on the Spider and BIRD datasets show that the method improves execution accuracy and efficiency scores, achieving better results.

Keywords. Text-to-SQL, Prompt Learning, Large Language Models, Natural Language Processing, Intermediate Representation

1. Introduction

The text-to-SQL task converts natural language questions into executable SQL queries, enabling non-technical users to interact with relational databases. Traditional approaches rely on deep neural networks trained via encoder-decoder frameworks, yet require costly annotated datasets [1-2]. Additional ontology-driven methods leverage semantic mappings but demand manual schema engineering [3-4]. Recent advances in large language models (LLMs) like GPT and T5 show promise for text-to-SQL through prompt engineering. These models excel in few-shot scenarios by capturing SQL semantics without extensive training [5]. However, complex queries expose critical limitations: multi-table joins often lead to structural errors.

To address the challenge, we propose a method integrating problem decomposition, Query Intermediate Representation (QIR), and dynamic example selection. First, a schema linking module filters relevant database elements. Queries are then classified as simple (single-table) or complex (multi-join), triggering differentiated SQL generation. For complex cases, QIR enhances semantic alignment while leverage the sensitivity of

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large models to examples, further enhancing accuracy while simplifying template design. Evaluations on Spider and BIRD benchmarks demonstrate significant improvements in execution accuracy (87.3% on Spider).

The paper is divided into five sections. Section 2 provides a review of existing methods for the text-to-SQL task. Section 3 details the proposed method framework. Section 4 introduces the experimental settings and results analysis. Finally, Section 5 concludes the research and outlines future directions.

2. Related Work

Early text-to-SQL research focused on encoder-decoder architectures trained on annotated datasets. Sequence-to-sequence models [1-2] generated SQL by rejecting invalid tokens during decoding, while Abstract Syntax Tree (AST)-based methods [6-7] enforced syntactic validity through grammar rules. Self-supervised techniques [8-9] further improved robustness by leveraging input data for self-assessment. However, these approaches require large-scale labeled data and suffer from high computational costs, limiting scalability.

In addition, there are ontology-based methods. The method in paper [10] uses ontology alignment to convert natural language into SPARQL queries, adapting to user via personalized ontologies. The method in paper [11] employs dynamic ontology learning to automate query translation from database schemas for specific domains. However, both require manual ontology engineering, hindering their practical deployment.

Recent LLMs like GPT-4 revolutionized text-to-SQL through prompt learning. The MCS-SQL [12] model introduces a multi-generation and multi-selection strategy, exploring a broader answer space and effectively aggregating results. ACT-SQL [13] focuses on automatically generating chain-of-thought prompts, reducing the need for manual annotation. DIN-SQL [14] decomposes complex SQL queries into sub-problems and employs a self-correction mechanism to iteratively improve answers. However, these methods often rely on fixed templates and complex modules, which can lead to connection errors when dealing with complex queries involving multi-table joins and nested structures.

3. Method

The model includes three modules, with the overall architecture shown in Figure 1.

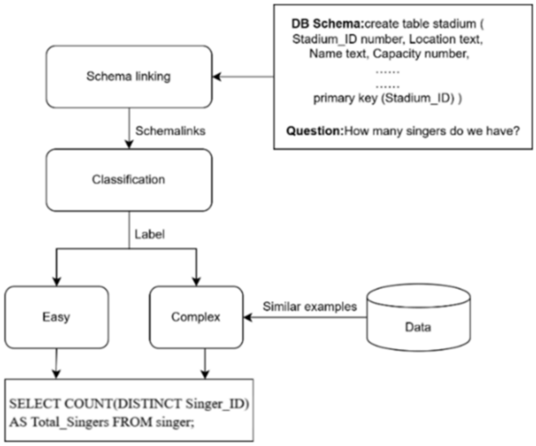

Figure 1. Overall Model Architecture.

The model first performs schema linking to filter out tables and columns related to the query from the database schema, excluding irrelevant parts. Then it classifies the query, dividing it into simple or complex queries based on whether it requires join operations. Finally, it generates SQL differentially. For simple queries, the model directly uses the output of schema linking and simple examples to generate SQL statements; for complex queries, the model introduces intermediate representation and dynamic example selection strategy to improve the accuracy and efficiency of SQL generation.

3.1. Database Schema Style and Schema Linking

Given a database schema, strong LLMs can translate simple natural language queries into correct SQL queries. The input format of the database schema significantly impacts LLM performance. We use a "Create (EoC)" schema style, which describes tables and columns using SQL's "Create table" statement. "EoC" stands for "End of Column," indicating that primary and foreign key information is added after each column. This style includes column type information, making it more realistic.

In text-to-SQL research, schema linking is crucial. It involves matching entities and concepts in natural language questions with database tables and columns. This connection guides the selection of relevant schema items, improving query accuracy and ensuring the generated SQL reflects user intent. We designed a schema linking module in the Create (EoC) style, using chain-of-thought prompts to select corresponding columns, foreign keys, and entities for each name in the question. When providing the schema to LLMs, we also include the selected columns, foreign keys, and entities through schema linking.

3.2. Query Classification Module

Multi-table joins involve complex database structures and semantic information processing, which are prone to inconsistent join errors and missing join errors. Inconsistent joins may result in an empty result table or a table containing all rows, leading to unexpected query results; missing join errors refer to the failure to correctly establish a connection between tables that should be joined, causing some data rows that should be associated to be excluded from the final result set.

To address the issues that may arise in multi-table joins, we design a query classification module that divides all queries into two categories: simple and complex. Simple queries involve operations on a single data table and do not require joins; complex queries involve joins and require more detailed strategies to ensure the accuracy of join conditions. The specific requirements are as shown in Figure 2.

Classification Prompts

For the given question, classify it as easy or complex based on JOIN. If need JOIN: predict COMPLEX elif don't need JOIN: predict EASY

DB Schema: create table stadium (Stadium_ID number, Location text, Name text, Capacity number, Highest number, Lowest number, Average number, primary key (Stadium_ID))
...

Question: How many singers do we have?

Schema Links: [singer.Singer_ID...]

Your answer: Let's think step by step.

Figure 2. Classification Prompts.

3.3. SQL Generation Module

SQL is mainly used for relational database queries rather than direct mapping of natural language meanings. For complex queries, dealing with the "mismatch" between natural language questions and SQL statements is particularly important. We design differentiated SQL generation processes based on the characteristics of different query categories.

In the process of generating simple SQL statements, the model can directly utilize the results of schema linking and simple examples to generate SQL statements. This process can be represented as Equation (1).

$$S = LLM(Q, D, S, E) \tag{1}$$

In Equation (1), Q is the natural language query text, D is the complete database schema, S is the relevant database schema, and E is a list of simple examples that follows the format $[(Q_1, S_1, A_1), \ldots, (Q_m, S_m, A_m)]$, with A_i being the correct SQL statement for the *i-th* example. Specific prompts are as shown in Figure 3a.

Easy SQL Generation Prompts

Employ the schema links to construct the SQL queries for each question.

DB Schema: create table stadium (Stadium_ID number, Location text, Name text, Capacity number, Highest number, Lowest number, Average number, primary key (Stadium_ID))
...

Question: How many singers do we have?

Schema Links: [singer.Singer_ID...]

Simple example: ...

Your answer: Let's think step by step.

(a) Easy SQL Generation Prompts.

Complex SQL Generation Prompts

Utilize the schema links and intermediate representation to formulate the SQL queries for every question.

DB Schema: create table stadium (Stadium_ID number, Location text, Name text, Capacity number, Highest number, Lowest number, Average number, primary key (Stadium_ID))
...

Question: How many singers do we have?

Schema Links: [singer.Singer_ID...]

QIR Intermediate Representation:
SELECT: SELECT COUNT(*) FROM singer;
RETURN: The result of the SELECT statement.

Examples of semantic proximity: ...

Your answer: Let's think step by step.

(b) Complex SQL Generation Prompts.

Figure 3. SQL Generation Prompts.

When dealing with complex queries, we need to consider more factors, including how to identify and use columns and foreign keys to join two or more tables, and whether subqueries or set operations (such as EXCEPT, UNION, INTERSECT) are needed. To solve the challenges in complex queries, we adopt the intermediate representation method QIR proposed in [15]. This method has been proven to effectively improve the accuracy and interpretability of SQL generation.

LLMs produce significantly different outputs under the influence of different examples. We take advantage of this characteristic of LLMs and use a strategy based on problem similarity to select the top k most similar problems to the natural language query from the dataset as examples embedded in complex queries, helping LLMs to generate more accurate results when facing complex connection queries.

The process of generating complex SQL statements can be formulated as Equation (2).

$$S = LLM(Q, D, S, I, E) \tag{2}$$

In Equation (2), I is the intermediate representation QIR, and E is a list of simple examples that follows the format $[(Q_1,S_1,I_1,A_1),\ldots,(Q_k,S_k,I_k,A_k)]$, with A_i being the correct SQL statement for the *i-th* example. Specific prompts are as shown in Figure 3b.

4. Experiments and Results Analysis

The proposed system is developed in Python 3.10, leveraging the Hugging Face transformers library for LLM integration. We use GPT-4 as the LLM and access it through the OpenAI API. To ensure that the generated SQL queries have strict syntactic structure, we set the temperature parameter to 0. For all modules, the maximum token number is set to 500. In dynamic example selection, the number of examples k is set to 5. All experiments were completed on a PC with the Windows 10 operating system, 64GB of memory, an Intel Core i9-10980XE CPU, and an NVIDIA GeForce RTX 3090 GPU.

4.1. Datasets

The Spider benchmark is a widely used dataset for evaluating cross-domain text-to-SQL models. It includes 10,181 natural language questions paired with 5,693 SQL queries across 200 databases in 138 domains. Each domain has multiple tables with complex schemas. The dataset is split into 6,659 training samples from 146 databases, 1,034 validation samples from 20 databases, and 2,147 test samples from 34 databases, with no overlap between partitions for rigorous evaluation.

BIRD introduces real-world database complexity and external knowledge dependencies, containing 12,751 question-SQL pairs linked to 95 large-scale databases (33.4 GB) in 37 domains like blockchain and healthcare. Unlike Spider, BIRD integrates auxiliary resources such as domain-specific terminology, numeric reasoning rules, and synonym mappings. Its SQL queries often involve nested operations and multi-step reasoning, making them more structurally complex.

Both benchmarks use execution accuracy (EX) as the primary metric, verifying predicted SQL outputs via database execution. BIRD also introduces the Valid Efficiency Score (VES) to measure the runtime performance of valid SQL queries, emphasizing practical applicability.

4.2. Experimental Results

The experimental results on the Spider dataset are shown in Table 1. Our method demonstrates significant performance improvements, particularly in EX. On the development set, our method achieved 87.5%, outperforming the other prompt-based methods by 0.7%. On the test set, our method also performed exceptionally well, achieving the highest execution accuracy, with significant improvements compared to the other prompt-based methods.

Table 1. Execution accuracy (EX) on the development and test sets of Spider.' - ' indicates that the model did not report the performance on the test set.

Model	Dev	Test
GPT-4 (zero-shot)	74.6	-
DIN-SQL+ GPT-4	82.8	85.3
DAIL-SQL+ GPT-4	84.4	86.6
MAC-SQL + GPT-4	86.8	-
QC-SQL + GPT-4 (Ours)	87.5	87.3

The experimental results on the BIRD dataset are shown in Table 2. Despite the BIRD dataset containing more complex SQL queries, our method also shows its superior performance, significantly outperforming the other prompt-based methods in both EX and VES. On the test set, our method achieved 60.3% EX and 68.4% VES, surpassing the other prompt-based methods by 1.4% and 1.8%, respectively.

Table 2. Execution accuracy (EX) and Valid Efficiency Score (VES) on the development and test sets of BIRD

Model	Dev		Test	
	EX	VES	EX	VES
GPT-4(zero-shot)	46.4	49.8	54.9	60.8
DIN-SQL+GPT-4	50.7	58.8	55.9	59.4
DAIL-SQL+GPT-4	54.8	56.1	57.4	62.0
MAC-SQL+GPT-4	57.7	58.8	59.6	67.7
QC-SQL (Ours)	58.3	60.2	61.0	69.5

5. Conclusion

LLMs have demonstrated significant potential in text-to-SQL tasks, yet prompt-based approaches often struggle with complex queries. This paper proposes a novel method integrating problem decomposition, intermediate representation QIR, and dynamic example selection, which effectively addresses challenges in multi-table joins and nested queries. Experimental results on the Spider and BIRD benchmarks validate the superiority of our approach. Specifically, on the Spider test set, our method achieves an EX of 87.3%, outperforming existing prompt-based methods. For the BIRD dataset, our model attains 61.0% EX and 69.5% VES. By using intermediate representation, and dynamic example selection strategies, the model can flexibly adapt to different query types based on input characteristics, improving efficiency and performance. Further research will focus on designing more intelligent query classifiers that can automatically learn and adapt to the characteristics of different types of queries, reducing the need for manually defined rules.

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Large Language Model-Driven Health Information Services: Opportunities, Scenarios, Risks and Paths

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Abstract. The new generation of information technologies such as artificial intelligence and big data have become the accelerators for the transformation and high-quality development of the medical and health industry. The big language model represented by ChatGPT is a new round of growth point for the development and application of artificial intelligence, bringing subversive changes to the field of information services. It is of great significance to enable it in health information services. This paper analyzes the opportunities, scenarios and risks of health information service driven by big language model. Guided by system theory, it constructs a health information service framework driven by big language model based on WSR methodology and presents it in the form of a three-dimensional spatial structure by comprehensively considering the three key elements of Wuli, Shili and Renli, in order to provide the overall system architecture design and feasible solution path for the health information service practice under the emerging artificial intelligence technology environment.

Keywords. Large language model, ChatGPT, generative artificial intelligence, WSR methodology, health information service

1.Introduction

It has become an important trend to use new generation information technologies such as artificial intelligence, big data, cloud computing, mobile Internet, and the Internet of Things to empower the development of the medical and health industry. Traditionally, people mainly get health information through face-to-face communication with medical workers, but this way is strictly limited by time and space, poor convenience, high economic cost and time cost, and tends to one-way indoctrination. The rapid development and wide popularization of Internet technology has brought convenience to the public's access to health information, and the Internet has become the main channel for people to obtain health information [1]. Under the environment of big data, the health information on the Internet shows an explosive growth trend, with the characteristics of huge amount of data, various types, complex structure and uneven quality, which brings serious challenges to health information services. The large language model represented by ChatGPT is a subversive innovation technology in the field of artificial intelligence. It is of great significance to apply it organically in the

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medical and health industry and converge it into intelligent, personalized and high-quality health information services.

2.Related works

With the rapid progress of artificial intelligence technology, large language model has shown great application potential in the field of medical health with its powerful natural language processing ability and deep learning ability. The application of large language model to the medical and health field is a current research hotspot, and the relevant representative studies are as follows.

Kung et al. evaluated ChatGPT's performance on the United States Medical Licensing Examination (USMLE) and found that ChatGPT was able to pass or nearly pass the USMLE without any special training or reinforcement [2]. Sarraju et al. created 25 questions including risk factors, test results, and medication information, and then evaluated ChatGPT on these questions, and the results showed that the AI model responded appropriately to 21 (84%) questions [3]. Dubin et al. found that for 20 questions related to total knee replacement and total hip replacement, ChatGPT's answers were more authoritative than Google's web search results. 75% of the former's answers were provided by government websites, while 65% of the latter's search results were provided by commercial websites [4]. Van Bulck et al. asked 20 cardiologists to evaluate the credibility, value, and risk of the answers generated by ChatGPT for virtual patient questions. The results showed that: Experts generally believe that the answers generated by ChatGPT are trustworthy and valuable, with 40% of experts believing that ChatGPT's answers are more valuable than the information provided by Google [5].

The application of large language models in the field of medical health can not only improve the quality and efficiency of medical services, but also promote the development of medical education and scientific research. With the continuous progress of technology and the continuous expansion of application scenarios, the application prospect of large language model in the medical and health field will be broader.

3.Methods

Health information service driven by large language model is a typical complex system project, which requires the collaboration of engineers with different professional knowledge and skills to provide intelligent, accurate and high-quality health information services for patients and the public by using various types of hardware and software resources in accordance with a series of systematic processes. To solve the problem of system engineering, it is necessary not only to adhere to the system thinking and system concept, but also to use the system methodology flexibly. System thinking and system concept require us to look at problems and things from the perspective and pattern of overall comprehensiveness, universal connection, development and change, and comprehensively analyze and examine the elements, structure, function and environment of the system.

System methodology is a general procedure, logical step and basic method that should be followed to analyze and solve problems in system development, operation and management practice. It provides logical mode at the thinking level and procedure steps at the operational level for solving problems such as planning, design, manufacturing, use and organization management of large-scale complex systems. In the process of system engineering research and application, domestic and foreign experts and scholars have explored and summarized a variety of scientific and effective working methods and procedures. After a comprehensive comparison of these methodologies, this paper builds a large-language model-driven health information service framework based on WSR system methodology [6].

WSR methodology is short for Wuli-Shili-Renli (W-S-R), and its basic idea is that when solving complex system problems, it is necessary to comprehensively and fully consider and use the three important elements of “Wu” (things), “Shi” (events), and “Ren” (people). WSR methodology is systematic, comprehensive, scientific and operable, and is a general "Oriental system management methodology", which has been widely used in many disciplines by researchers at home and abroad.

4.Results & Discussion

4.1 Large Language Model-Driven Health Information Services: Opportunities

The large language model has the technical characteristics and advantages of intelligent emergence ability and huge knowledge reserve, strong learning and reasoning ability, excellent generalization ability and portability, excellent dynamic generation and interaction ability, extraordinary natural language understanding and generation ability, multi-modal fusion and multi-language support, multi-task processing, etc. It has broad application space and huge development potential in the medical and health industry and health information service field, and can effectively respond to the health information service needs of patients and the public in the big data environment.

Responses of large language models to the authority of health information services. As the main channel for patients and the public to obtain health information at present, the Internet platform is an open big data resource library. Authoritative medical experts, netizens, self-media and other subjects can enter the resource library and be retrieved when they publish various health information on platforms such as Tieba, Weibo and Douyin. Although this allows the content of relevant resources on the Internet platform to be continuously updated and increased to a certain extent, it also provides a hotbed for the breeding and dissemination of unprofessional and unauthoritative health information. Large language models can selectively include reliable corpus data for training models, and the knowledge base formed is relatively closed, and Internet users, we-media and other subjects cannot write health information with mixed quality. This mechanism ensures the authority of health information services.

Responses of large language models to the intelligence of health information services. The large language model represented by ChatGPT is a new frontier technology of artificial intelligence, and its research and application have made remarkable achievements in the world. The introduction of large language model, a disruptive and innovative artificial intelligence technology, into the medical and health industry can effectively improve the intelligence level of health information services by using its powerful learning, understanding, reasoning, generation capabilities and huge knowledge capacity.

Responses of large language models to interactivity in health information services. At present, the forms of health information services provided by Internet platforms for patients and the public can be summarized as follows: information retrieval, knowledge navigation, information push and knowledge Q&A. The first three forms have obvious shortcomings in interactivity. Although the current Internet platform provides users with a better interactive service form of knowledge question and answer, it is mainly through the online communication between users and doctors in the dialog box, the degree of automation and intelligence is low, and the response time is not enough, and the service effect often depends on the knowledge reserve, ability level and responsibility of doctors. The large language model adopts the form of intelligent information service with strong interactivity, such as automatic question answering, which can quickly and automatically aggregate and generate answers to user questions to improve user experience.

Responses of large language models to the precision of health information services. The large language model can effectively improve the current situation that Internet platforms represented by search engines cannot provide accurate and personalized health information services for patients and the public, mainly due to: Large-scale knowledge capacity, the large language model learns and fits on massive text data, contains rich information and knowledge, which enables the model to use a wide range of background knowledge when answering user questions; Strong semantic understanding ability. Large language models can understand the context and semantics of natural language through pre-training and fine-tuning, so as to better understand users' questions and intentions and provide more accurate answers; Excellent interactive ability, large language model with coherent and fluent question and answer interaction attributes, can dynamically guide users to express information needs.

4.2 Large Language Model-Driven Health Information Services: Scenarios

Health care is one of the industries where large language models have the most far-reaching impact. As a new growth point of industrial development, large language model can be applied and integrated into many aspects of medical and health care. It can serve doctors, nurses, patients, the public, disease prevention and control personnel, scientific researchers, medical and health managers and other objects. This paper mainly explores health information services for patients and the public, and related business scenarios mainly include the following.

Information service for residents' health literacy. Health literacy is an important indicator to measure and evaluate the level of basic public services and people's health in a country or region, and an important determinant of health. It is closely related to population life expectancy and health status, and is a comprehensive reflection of the level of economic and social development. The World Health Organization (WHO) defines health literacy as the cognitive and social skills that determine an individual's motivation and ability to acquire, understand, and use information to promote and maintain health. From the concept of health literacy, we can intuitively see the key role of information and information service in improving residents' health literacy. It can be based on the large language model to popularize the basic knowledge and skills that the public should have at the present stage of healthy lifestyle and behavior, and disseminate authoritative and reliable health information, so as to help the majority of residents better manage their health conditions and prevent diseases.

Information service for chronic disease health management. Chronic diseases such as hypertension, diabetes, stroke, coronary heart disease and COPD are the leading causes of death and disease burden worldwide. China has more than 300 million chronic diseases, and the proportion of deaths and disease burden caused by chronic diseases has reached more than 85% and more than 80% respectively. Chronic diseases have the characteristics of complex etiology, hidden onset, long course, high rate of repeated visits, many complications, easy to repeat and difficult to cure, etc. Patients with chronic diseases usually need long-term drug treatment and scientific health management. In this process, patients need dynamic and continuous access to health information related to medication, examination, diet, treatment, exercise, follow-up visits and care for their disease. Based on the large language model, health consultation, behavioral guidance, health advice and psychological support can be provided to patients with chronic diseases to help them better manage chronic diseases and improve their quality of life.

Information service for hospital medical guidance. Before the patient goes to the hospital for medical treatment, he or his family members may inquire in advance about the hospital's introduction, geographical location, transportation mode, reception time, the department corresponding to the current symptoms and diseases, the professional background, good field and scheduling of doctors in the department and complete the registration. Patients to the hospital, may also involve registration, treatment, inspection, printing reports, take medicine, payment, hospitalization, discharge and medical insurance reimbursement and many other links, patients in the process of each link may need to obtain relevant information in order to successfully complete. Therefore, these multi-dimensional information of various hospitals can be integrated into the large language model and updated in time, so as to provide patients and their families with the whole process from entering the hospital to leaving the hospital and all-round medical treatment guidance, so as to help patients more smoothly complete medical treatment activities and improve patient satisfaction.

Information service for public health emergencies. In recent years, the number of public health emergencies around the world has shown a gradual increasing trend. The most typical is the outbreak of COVID-19 in 2019, which has caused hundreds of millions of infections and millions of deaths globally, making it one of the deadliest epidemics in human history. In the face of public health emergencies such as major infectious diseases, mass diseases of unknown cause, major food and occupational poisoning, the public urgently needs to have relevant information to ease panic and anxiety, take necessary protective measures and cooperate with the emergency response work of government departments. It can provide accurate, timely, comprehensive and reliable information support for the public based on the large language model, including disease prevention and popularization, real-time data update, emergency contact information, medical resource distribution, false information refuting rumors, mental health consultation and other aspects.

4.3 Large Language Model-Driven Health Information Services: Risks

While large language models bring great opportunities to health information services, they also inevitably bring some new problems and challenges. Before applying the large language model to the specific scenario of health information service field, it is necessary to conduct a comprehensive and systematic analysis of these risks and challenges. Then take targeted measures and strategies to deal with it, to ensure that the large language model can play a positive role to the maximum. The possible risks and challenges of health information service driven by large language model are mainly reflected in the following aspects.

Black box model and trust risk. The big language model is essentially a deep neural network containing hundreds of billions of parameters, which is a typical black box model. Its internal operation mechanism is extremely complex and lacks transparency, and it can quickly return answers to user questions. However, it is very difficult to understand why the big language model returns a certain answer to a certain question. And the answer to the same question may not be the same. Although patients and the public cannot understand why doctors make corresponding responses and decisions when they communicate with doctors face to face (because the doctor's brain is itself a complex neural network and black box), when people interact with large language models, they are faced with machines that are naturally separated from humans. To some extent, this will reduce the user's trust in the machine [7]. In addition, large language models may also have the phenomenon of "serious nonsense", that is, generating content with errors or deviations, which will also have a certain negative impact on its popularization and use.

Data infringement and copyright disputes. The excellent text understanding and generation ability of large language models cannot be separated from a large number of high-quality training corpus. As mentioned above, the training data of ChatGPT reaches more than tens of TB, and the capacity of the training set is larger if the model involves multiple modes such as pictures, audio and video. The developer of large language model collects and uses massive data resources from books, journals, news media and other sources to train the algorithm model, which has the risk of infringement, and forms a huge and opaque deep neural network model after the training, which is difficult to discover and prove the infringement facts [8]. In January 2023, Getty Images sued Stability AI, an artificial intelligence company, for using more than 12 million photos owned by the company to train Stable Diffusion AI, an image generation model, without permission. In addition to the possible infringement of model training data, the copyright ownership of the content generated by the large language model is also controversial, and the ownership of interests of investors, program developers and users of AI systems is not easy to clarify.

Algorithmic discrimination and data security. The massive data on Internet forums and social media is one of the important sources of large language model training corpus. Musk, chairman of social media company Twitter, has repeatedly accused Microsoft, OpenAI and other companies of illegally using Twitter data to train large AI models, and limiting the maximum daily Twitter visits of different types of users to prevent data from being crawled. As a typical user generated content (UGC), these network big data contain a large number of gender, ethnicity, region, race, age, education, family status, disease and physical defects with discrimination or prejudice content. If this data is used to train large language models, then the output of AI systems when interacting with users will inevitably show algorithmic discrimination. In addition, the network text for training the large language model may also contain personal privacy content, the information collected during the operation of the model may include personal privacy, trade secrets, and state secrets, and the user information used by the model for subsequent iterative training may easily lead to privacy disclosure and data security problems.

4.4 Large Language Model-Driven Health Information Services: Paths

For the black-box model and trust risk, it is necessary to automatically label the original source of data in the form of literature citations for the answers generated by users' questions, so as to facilitate the backtracking of patients, the public and regulatory agencies. As far as possible, complete sentences in the text data are aggregated to form the answer to the question. As far as possible, the computer can avoid automatically generating sentences based on knowledge units such as words and phrases, which may lead to the formation of biased or wrong answer content.

For data infringement and copyright disputes, it is necessary to sign data cooperation agreements with publishing houses, database platforms and online health communities with massive data resources, such as People's Medical Publishing House, Science Publishing House, Web of Science, Elsevier, CNKI, Haofu Online, etc. Comply with the policies, systems, laws and regulations of the country and region on the copyright of artificial intelligence-generated content, and do a good job in compliance construction.

In order to deal with algorithm discrimination and data security, authoritative and reliable corpus data should be used to train large language models, such as the book resources of authoritative publishing houses such as People's Medical Publishing House and Science Publishing House, the literature materials of important journals such as SCI, CSCD, Peking University Core and "Zhonghua Brand" medical journals, and the authoritative replies of real-name certified doctors in online health communities. Data classification, isolation, desensitization, encryption, destruction and other measures are adopted to ensure user privacy and data security.

Based on theories, methods and technologies in the fields of artificial intelligence and information system, this paper constructs a health information service framework driven by large language model based on WSR system methodology, as shown in Figure 1. The model is a three-dimensional spatial structure composed of Wuli dimension, Shili dimension and Renli dimension. Wuli dimension is the hardware and software resources needed to realize the health information service driven by large language model, including data, algorithm, knowledge and computing power. Shili dimension is a series of systematic processes that need to be completed, including data preparation, model training, application deployment and performance optimization. The Renli dimension refers to the human resources to be configured, including data engineer, algorithm engineer, knowledge engineer, and software engineer.

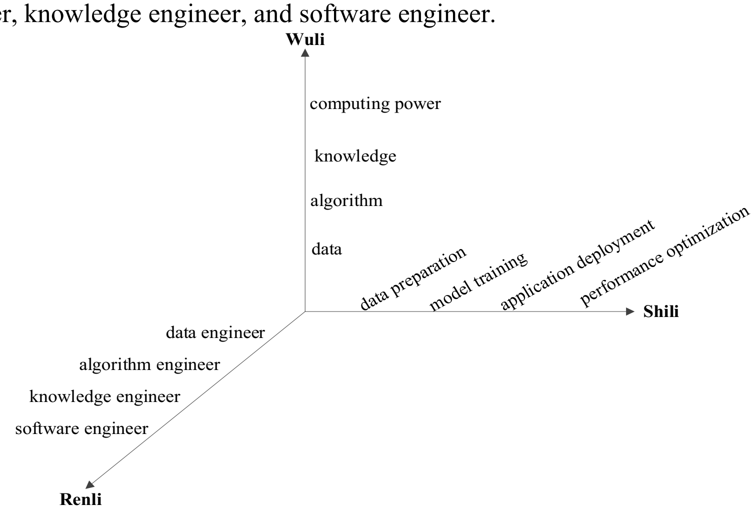

Figure 1. Health Information Service Framework Driven by Large Language Model.

Wuli Dimension. Data, algorithm, knowledge and computing power are the four key elements in the construction and development of a new generation of artificial intelligence: (1) Big data is one of the important reasons for the improvement of the performance of artificial intelligence systems in recent years, and the pre-training and fine-tuning of large language models require massive and high-quality data resources, mainly from books, journals, encyclopedias, news reports, online health communities, etc. (2) At present, the key algorithm of many large language models is the end-to-end deep neural network Transformer, which uses the attention mechanism to capture context information and takes the encoder and decoder as the whole architecture [9]. At present, there are a large number of free and open source libraries to implement this algorithm. Such as OpenNMT, Fairseq, Tensor2Tensor, Hugging Face Transformers, GluonNLP, etc. (3) External knowledge base can be integrated into Transformer model through knowledge graph embedding, knowledge distillation, attention enhancement, joint training, etc., so that the large language model can better understand and process information in different fields. (4) The training and reasoning of large language models have very high requirements for computing power, storage and network, and can be based on a cloud computing platform with powerful computing resources and flexible resource management capabilities to meet the computing power needs of large language models, reducing expensive hardware expenses and complex installation and configuration links.

Shili Dimension. Data preparation, model training, application deployment, and performance optimization are the four key steps to build and apply a large language model: (1) In the data preparation stage, it is necessary to collect the general corpus and medical and health corpus required for model training and fine tuning by means of web crawler, API interface call and database connection access, and carry out pre-processing operations such as cleaning, word segmentation, special mark addition, vocabulary establishment, filling and truncation, sample generation, and location embedding. (2) In the model training stage, the model is first pre-trained on a massive general corpus so that the model can learn the universal features, syntactic structure and word meaning relations of the language [10]. Then, the model is fine-tuned on the corpus in the medical and health field to make the model more suitable for the tasks in the health information service field. Finally, validation sets or cross-validation are used to evaluate the performance of the model and adjust and improve it. (3) In the application deployment stage, the large language model will be deployed and integrated into platforms such as search engines, online health communities, hospitals and the official websites of the Health and Health Commission, or special mobile apps and wechat mini programs will be developed to provide health information services for patients and the public. (4) In the performance optimization stage, the performance of the large language model is continuously monitored, and it is updated and improved according to data changes and user feedback, such as optimizing model structure, adjusting model hyperparameters, data enhancement, etc.

Renli Dimension. Data engineer, algorithm engineer, knowledge engineer and software engineer provide human resources support for the domain application of large language models: (1) Data engineer, whose tasks and responsibilities include data collection, cleaning and preprocessing, evaluation of data quality and consistency, design and implementation of data transmission pipelines, data labeling and feature marking, design of reasonable data storage and management schemes, optimization of data loading and processing speed, timely processing of abnormal data, and ensuring that data acquisition and utilization comply with laws and regulations. (2) Algorithm engineers, whose tasks and responsibilities include model architecture design, algorithm development and optimization, hyperparameter tuning, design and optimization of transfer learning and pre-training strategies, design and implementation of adversarial training strategies, development of hyperparameter optimization and model selection algorithms, and enhancement of model interpretability. (3) Knowledge engineer, tasks and responsibilities include knowledge collection and integration, entity linking and relationship extraction, knowledge cleaning and standardization, design of knowledge representation models and knowledge base construction, knowledge quality and accuracy assessment, knowledge base update and maintenance, etc. (4) Software engineer, whose tasks and responsibilities include developing health information service platform, mobile application APP or wechat mini program based on large language model, deploying application program, designing fault tolerance mechanism and monitoring system, ensuring stable operation of system, completing system maintenance and update, etc.

5.Conclusion

The main contribution and innovation of this paper lies in the construction of a health information service framework driven by a large language model based on WSR methodology, in order to provide an overall system architecture design and a feasible solution path for search engine companies, online health communities, hospitals and health commissions to carry out health information service practice under the environment of emerging artificial intelligence technology. Future research directions mainly include the following aspects: analyze the big language model based on specific health information service cases and data, develop a big language model-driven health information service platform, build a new generation of big language model jointly driven by data and knowledge, and explore the risk mitigation and collaborative governance system for the application of big language model.

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Research on the Identification and Intersecting Influences of Foreign-Related Factors in Public Security of Border Areas

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Abstract: The border areas face diverse security risks, necessitating a systematic identification of key influencing factors and clarification of their hierarchical relationships and interconnections. Through literature surveys and expert scoring, this study constructs an index system for foreign-related factors affecting public security in the border areas. It employs the DEMATEL method to identify key factors, the ISM method to analyze hierarchical relationships and pathways of influence, and the MICMAC analysis to examine the driving forces and dependencies among factors. The results show that among the 16 influencing factors, three, including the Geopolitical Landscape, are root factors; nine, including Culture and Values Transfer, are intermediate factors; and four, including Ethnic and Religious Issues, are surface factors, with all factors being interwoven. The study suggests consolidating the foundation of "geopolitics, economy, and international relations" integrating internal and external security development factors, building a border-specific security pattern, and implementing the overall national security concept.

Keywords. Border areas; Foreign-related influencing factors; DEMATEL-ISM-MICMAC; Collaborative Governance

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1. Introduction

The Report of the 20th National Congress of the Communist Party of China has put forward clear requirements for further strengthening China's public security and social governance under the new situation. The key is to grasp the new key points and characteristics, promote the innovation and improvement of relevant mechanism frameworks, work systems, and working models, effectively enhance the capability to deal with relevant security risks, and effectively build a bulwark to prevent the transmission of relevant risks to the field of political security[1].The border areas, as an integral part of the national governance system, have always occupied a special strategic position in the overall situation of the Party and the country. With the deepening of China's economic globalization and the vigorous implementation of policies such as the “Belt and Road Initiative,” the border ethnic regions not only shoulder multiple missions but have also become an important window for China's opening-up and a vital node for international exchanges. However, influenced by the interweaving of geography, history, ethnicity, economic development, and multiple foreign-related factors, social governance in these regions, especially the handling of public emergencies, exhibits particularity and complexity. This has led to the diversity and challenging nature of public security issues in these areas, which have become pressing problems that need to be resolved in China's long-term development process. Under the new situation, it is necessary to re-examine the timeliness and particularity of land-border security threats and to identify and assess the main security threats, their characteristics, impacts, and trends[2]. Based on the multiple special characteristics of the border areas, public security and governance capabilities should no longer be confined to a reactive approach that addresses problems in a piecemeal manner. Instead, they should be more flexible and forward-looking in adapting to the new challenges brought about by rapid environmental changes[3].

Based on the DEMATEL-ISM-MICMAC analysis method, this study conducts an in-depth analysis of the foreign-related factors of public security, determines the risk probability of mixed factors, and identifies the public crisis risk contribution rate of each factor through a multi-factor and multi-order influence analysis model. The innovations of this paper lie in the following aspects: the DEMATEL-ISM-MICMAC method is employed to comprehensively analyze the cross-influences of foreign-related factors of public security in border areas from both micro and macro perspectives, taking into account the impacts of both direct and indirect factors. The study identifies key factors, provides a detailed analysis of the cross-influences of foreign-related factors, categorizes these factors, proposes a corresponding classification model, specifies a list of cross-influencing factors, and offers practical and instructive policy recommendations.

2. Literature Review

The concept of public security and its application fields have been endowed with new meanings in the new era, due to the continuous changes in the international situation and the wide range of focus areas. From the perspective of “security,” it can be understood as encompassing both “security” and “safety”[4]. China's research in this area started relatively late. Professor Liu Yuejin defined it to cover both traditional and non-traditional security. It can be seen that public security in the general sense mainly refers to the safety risk management in the fields of domestic disaster prevention, mitigation and relief, production safety, public health, and social security. Although these aspects are related to national political, economic, cultural, and ecological security, the connection is relatively indirect, forming a weak association. Meanwhile, they are also related to the security risks of foreign countries, overseas areas, and the Belt and Road Initiative, but there is usually a distinction between domestic and foreign, which is an indirect connection. In contrast, border public security exhibits characteristics different from general public security. It is more significantly and directly linked to national security and has distinct attributes of national security. “To govern a country, one must first govern its borders.” In the new era, border public security plays a prominent role under the overall national security concept. Research on border security involves multiple aspects, including border security, the security of border residents, and identity security. At present, research on China's border security issues mainly focuses on border development, ethnicity, religion, stability, and China's relations with neighboring countries. Compared with general public security, border public security is directly related to national security and has distinct attributes of national security[5].The underlying logic of border security is national security, and the mission of border public security governance is of great significance. In order to accurately grasp the future development trend of border public security, it is imperative to be guided by the overall national security concept. As shown in Figure 1.

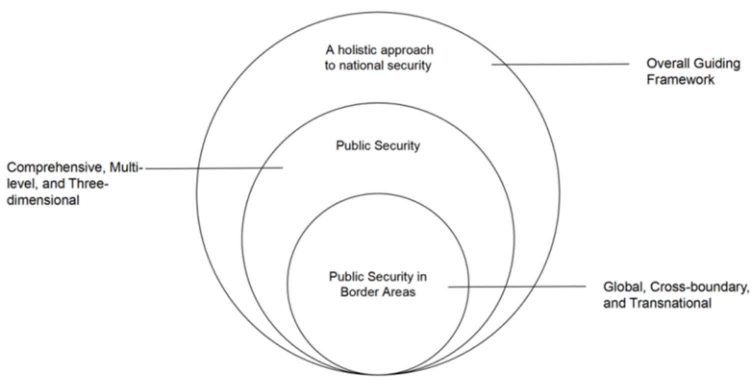

Figure. 1. Special Attributes of Border Public Security

The security situation of border areas dynamically changes with the evolution of historical and spatial contexts. In ancient times, the main research topics included the border governance policies of ancient Chinese dynasties that adapted to local customs, as well as the historical experiences of garrison farming and border defense throughout Chinese history. Today, against the backdrop of globalization, factors such as transnational crime, religious extremism, and separatist forces pose serious threats to the stability of border areas. Therefore, it is necessary to address these challenges through international cooperation and regional coordination. Currently, scholars analyse the influencing factors of border security from various angles. Zhong Guifeng et al[6]. analyse the challenges of border security from the perspectives of geopolitics and ethnic conflicts; Su Chang et al[7]. focus on the security threats in Central Asia; Li Xuebao et al[8]. explore the foreign factors in the governance of security in border ethnic areas; Jin Xiaozhe et al[9]. pay attention to the logic of the evolution of the U.S. discourse on human rights in relation to the border area; and Huang Mingtao et al[10].

present the current ethnic policy at different levels by analysing the influencing factors of the border area. Different levels present the current research progress of ethnic policy. It can be seen that the influencing factors of borderland security are complex and diverse, in which the types and development trajectories of foreign-related triggers of borderland public emergencies are also showing a trend of complexity, and the threatening factors from the fields of politics, economy, society and culture are intertwined with each other and cause and effect each other. The overall situation is characterised by complexity, comprehensiveness and multi-layeredness.

When analyzing complex systems with numerous factors and intricate interrelationships among them, appropriate methods may assist in identifying the root causes and exploring the internal connections and interwoven influences among these factors. Scholars such as Jin Weijian [11] and Li Gang[12] have employed systematic analysis methods like the Decision-Making Trial and Evaluation Laboratory (DEMATEL), Interpretive Structural Modeling (ISM), and MICMAC analysis. These methods can reveal the underlying causal logic and hierarchical structure of factors within complex systems, and identify key elements and logical connections among them.The influencing factors of public security in border areas are not only distributed across multiple levels, but also exhibit complex interrelationships among them. Current research in this area largely relies on qualitative methods such as questionnaire surveys, literature summaries, and case analyses, with relatively limited application of quantitative methods. Compared with traditional methods like questionnaires, the DEMATEL-ISM-MICMAC method can more deeply explore the degree of influence and interaction mechanisms among factors. This method, by constructing influence matrices and causal relationship models, can not only identify the key factors affecting public security in border areas, but also reveal how external factors trigger internal ones and the specific mechanisms of interaction between internal and external factors.

In the face of the coexistence of traditional and nontraditional risks, the decentralised borderland public security governance model has been difficult to meet the needs of the overall national security concept. Current research on border public security is mostly based on questionnaire surveys, literature summaries and case analyses, with fewer quantitative methods applied. Therefore, adopting a ‘systematic’ approach, integrating all kinds of resources and building a coordinated governance mechanism have become the key ways to deal with all kinds of risk factors and realise the governance of public security at the border. By strengthening international cooperation, improving laws and regulations, upgrading technical means and reinforcing emergency management, an allround, multilevel border public security governance system can be built to ensure the security and stability of the border areas and safeguard the overall security interests of the country.

3. Identification of Foreign-Related Influencing Factors and Construction of Indicator System for Public Security in Border Regions

3.1 Factor Identification Based on Literature Research

In the stage of extracting influencing factors, this study employs the literature review method to identify the key factors affecting public security in border areas. Based on the preset keywords and thematic search strategies, and through a rigorous literature screening process, 18 articles were ultimately determined as the foundational data sources for identifying the influencing factors[13].In the process of literature analysis, content analysis was employed to conduct an in-depth dissection of the selected literature, systematically extracting and summarizing the influencing factors mentioned in each document. Through multiple rounds of comparison and integration, a preliminary index system comprising 20 key influencing factors was initially constructed, including: anti-China forces agitation, foreign policy, level of political security, military strength, economic development level, religious propagation and exchange, cultural value export, and cross-border species invasion.

3.2 Determination of Influencing Factors

After the first round of literature sorting and screening, it is necessary to explore and adjust the rationality of the extraction of influencing factors, so as to lay a reliable foundation for empirical analysis. This paper invites a panel of experts to screen the list of barrier factors with rich experience in dealing with foreign-related security incidents and practical insights into collaborative governance. After fully understanding the literature sources and specific descriptions of each factor, the experts, through multiple rounds of discussion and judgment, divided the 16 factors into five levels, as shown in Table 1.

Table.1. List of Foreign-Related Influencing Factors on Public Security in Border Regions

aspect	code	foreign factors
Politics & Military	X6	Great Powers and Neighbourhood Relations
	X8	Geopolitical Landscape
	X13	International Public Opinion Trends
	X14	Military Strategic Deployment
Economy & Trade	X7	Economic Development
	X1	Openness and Co-operation
	X3	Cross-border Trade
Society & Culture	X15	Environmental and Ecological Impact
	X11	Public Health Issues
	X10	Culture and Values Transfer
	X2	Cross-border Population Mobility
	X12	Ethnic and Religious Issues
Security & Governance	X16	Ethnic separatist forces outside China
	X4	Emergency Response Mechanisms
	X9	Transnational Crime
Technology & Innovation	X5	Science and Technology Security Risks

4. Analysis of Foreign-Related Influencing Factors on Public Security in Border Regions

4.1 Research Methods

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is a system analysis approach proposed by scholars A. Gabus and E. Fontela from the Battelle Memorial Institute in the United States. It is designed to address complex and challenging system problems in the real world and is primarily applied at the micro level to determine the strength of direct and indirect relationships among factors[31].The Interpretive Structural Modeling (ISM) method was introduced by Professor Warfield, an American economist, in 1973 while exploring complex economic structures. It is mainly applicable at the macro level and can analyze the hierarchical influence relationships among factors within a system, simplifying complex system structures[32].Based on these methods, after establishing the ISM model, the MICMAC analysis can be employed. This approach directly utilizes the reachability matrix generated during the ISM model-building process for numerical analysis. Subsequently, based on the relevant numerical results, factors can be categorized to propose better improvement suggestions for the collaborative governance of public security in border areas.

4.2 Determination of the Comprehensive Influence Matrix

(1) Establishing the Direct Influence Matrix

Firstly, identify the various influencing factors and establish the direct influence matrix. This study employs a scale of 0 to 4 to more accurately assess the mutual influences among factors. Sixteen experts and professionals from the fields of border governance and national security were invited to use the Delphi method (expert survey method) to score the intensity of influence between each pair of factors. The intensity of influence was defined as follows: 0 (no influence), 1 (weak influence), 2 (moderate influence), 3 (strong influence), and 4 (very strong influence). The expert panel members were invited to compare each pair of influencing factors and score the degree of their mutual influence.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{bmatrix}$$

After data processing, the direct influence matrix was established. The questionnaire data collected were aggregated, and the scores from the 16 experts were averaged. The calculation results of the average values were rounded using the method of rounding decimal places and segmented processing[33][34], according to the values determined in Table 2. The direct influence matrix, after data processing, is shown in Table 2.

Table.2. Direct Influence Matrix

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16
X1	0	1	1	2	3	1	2	3	1	4	3	4	3	2	2	1
X2	1	0	1	3	2	3	1	0	1	2	2	3	4	2	3	3
X3	2	1	0	2	2	4	1	0	2	4	2	2	2	0	3	1
X4	3	2	1	0	2	3	2	2	1	3	4	4	3	2	4	1
X5	2	3	0	2	0	1	3	2	3	3	2	2	3	3	2	3
X6	4	2	2	3	1	0	1	2	2	4	2	4	2	4	2	2
X7	3	1	3	2	4	2	0	4	2	3	3	4	3	4	4	1
X8	2	1	4	3	4	2	4	0	3	4	3	4	4	4	3	2
X9	2	1	1	2	2	2	3	3	0	1	2	3	3	3	1	2
X10	4	3	2	4	2	2	2	0	2	0	2	3	3	3	4	2
X11	2	0	1	2	3	0	0	0	0	3	0	4	2	3	4	1
X12	4	0	0	2	4	1	0	0	1	4	3	0	4	3	2	1
X13	2	1	0	2	4	0	1	1	1	3	2	3	0	3	4	2
X14	1	0	2	2	4	1	1	1	1	4	2	4	4	0	3	4
X15	2	1	2	3	3	1	0	2	1	3	2	3	3	2	0	2
X16	2	3	1	4	1	1	1	1	2	4	2	2	1	1	3	0

(2) Establishment of the Normalized Influence Matrix

The direct influence matrix X is normalised to construct the canonical influence matrix D. The canonical formula is as follows:

$$D = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} x_{ij}} X(1)$$

Where $\max\limits_{1 \le i \le n} \sum_{j=1}^{n} x_{ij}$ represents the maximum sum of the rows.

(3) Establishment of the Comprehensive Influence Matrix

Based on the normalized influence matrix D, the comprehensive influence matrix T can be constructed through computation. The calculation formula is as follows:

$$T = D \times (I - D)^{-1}(2)$$

I is the identity matrix. Based on Equation (2), the normalized influence matrix D is calculated to derive the comprehensive influence matrix T.

4.3 Identification and Analysis of Key Factors

The comprehensive impact matrix T of public security in the border areas of China was calculated to find the degree of influence, the degree of being influenced, the degree of centrality and the degree of cause for each factor. Influence degree is the sum of the values of the rows corresponding to the influencing factor in the comprehensive influence matrix T; influenced degree is the sum of the values of the columns corresponding to the influencing factor in the comprehensive influence matrix T. The centrality is the sum of the influence degree and the influenced degree of the influencing factor in the comprehensive influence matrix T. The cause degree is the difference between the influence degree and the influenced degree of the influencing factor. When a factor is a cause factor, its cause degree shows a positive value, which means that it has a stronger driving effect on the other factors; on the contrary, when a factor is a result factor, its cause degree is negative, which indicates that it is more influenced by the other factors. Influence. The results of calculating the influence, influenced, centrality and cause degrees of each factor are shown in Table 3.

Table.3. Causal Influence Analysis of Foreign-Related Influencing Factors on Public Security in China's Border Regions

Influencing Factor	Influence Degree R	Influenced Degree C	Centrality N	Causality M	Factor Attribute
X1	2.389	2.637	5.026	-0.248	Resulting factors
X2	2.173	1.471	3.644	0.701	Causal factors
X3	2.003	1.416	3.420	0.587	Causal factors
X4	2.622	2.713	5.334	-0.091	Outcome Factors
X5	2.454	2.993	5.448	-0.539	Outcome Factors
X6	2.638	1.605	4.243	1.032	Causal factors
X7	3.072	1.528	4.600	1.544	Causal factors
X8	3.330	1.464	4.794	1.867	Causal factors
X9	2.267	1.614	3.882	0.653	Causal factors
X10	2.663	3.479	6.143	-0.816	Outcome Factors
X11	1.755	2.585	4.341	-0.830	Outcome Factors
X12	2.047	3.443	5.490	-1.395	Outcome Factors
X13	2.068	3.155	5.223	-1.087	Outcome Factors
X14	2.386	2.791	5.177	-0.405	Outcome Factors
X15	2.139	3.157	5.296	-1.017	Outcome Factors
X16	2.084	2.039	4.123	0.045	Causal factors

(1) Analysis of Influence and Affectedness

Influence is a key indicator that measures the strength of a factor's impact on other factors within a system. These factors cover multiple dimensions, including economic, political, and social aspects, and they are interrelated, collectively exerting significant influence on public security in border areas. Affectedness, on the other hand, reflects the extent to which a factor is influenced by other factors within the system. Through enhanced policy guidance, improved legal frameworks, and strengthened international cooperation, these critical factors can be ensured to play a positive role in promoting the long-term stability and prosperous development of border areas.

(2) Analysis of Centrality and Causality

Centrality is a numerical measure of the importance of an influencing factor. Its level directly correlates with the factor's impact on public security in China's border areas. A higher value indicates a stronger influence on border public security. For example, Culture and Values Transfer (X10) significantly impacts multiple factors within the system. Causality is a measure indicating whether a factor tends to drive other factors or is more susceptible to influence from other factors within the system. It also reflects the intensity of interactions among factors. For instance, Great Powers and Neighbourhood Relations (X6), Economic Development (X7), and Geopolitical Landscape (X8) largely drive other factors in the system, acting as “pillars.” Among the 16 factors affecting border public security, there are 7 causal factors and 9 resultant factors, as shown in Figure 2.

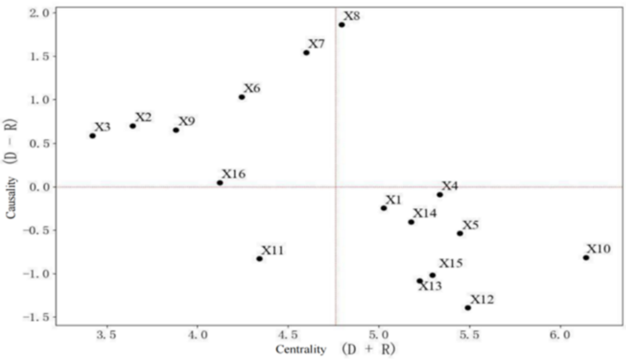

Figure.2. Centrality-Causality Diagram

4.4 Hierarchical Relationship Analysis

(1) Calculation of the Reachability Matrix

According to the integrated impact matrix T, the overall impact matrix F can be constructed. through equation (3), the overall impact matrix F of the influencing factors can be obtained, retaining three decimals, resulting in the mean value of the integrated impact matrix is 0.149, the standard deviation is 0.057, and the sum of 0.206 is set as the threshold value λ. According to equation (4), the reachability matrix K can be obtained.

$$F = T + I = f_{ij} (3)$$

$$K = \left[k_{ij}\right]_{n\times n} \quad k_{ij} = \begin{cases} 1, f_{ij} \geq \lambda \\ 0, f_{ij} < \lambda \end{cases} (4)$$

(2) Hierarchical division and multilevel hierarchical structural modelling

After finding the reachable matrix K, the next step is to hierarchise the influencing factors contained in the reachable matrix K. To establish the hierarchical structure of the influencing factors, we need to find out the reachable set R_i and the precedence set S_i of each factor, and then find the intersection of the two sets, if there is $A_i=R_i \cap S_i(i = 1,2,\cdots, n)$, and satisfy the $R_i = A_i$, then the intersection of all the influencing factors corresponding to the intersection of all the influencing factors for the first tier of the influencing factors, and then remove the rows and columns corresponding to this element of the reachability matrix K. Then continue to divide according to this principle to find out the second level influencing factors, and so on and so forth until all the influencing factors are divided into the second level. , and then continue to divide based on this principle to find the second level of influence factors, and so on, until all the influence factors are divided into different levels. Finally, five levels of elements are obtained, $L = [L_1, L_2, L_3, L_4, L_5]$.

According to the initial hierarchical structure of the influencing factors, a multi-layer recursive structural model of the foreign-related influencing factors of public security in China's border areas can be drawn, and because of the cross-layer influencing relationship between some of the influencing factors and all other layers, dummy nodes are introduced in order to make the hierarchical structure of the influencing factors more explicit, as shown in Figure 3.

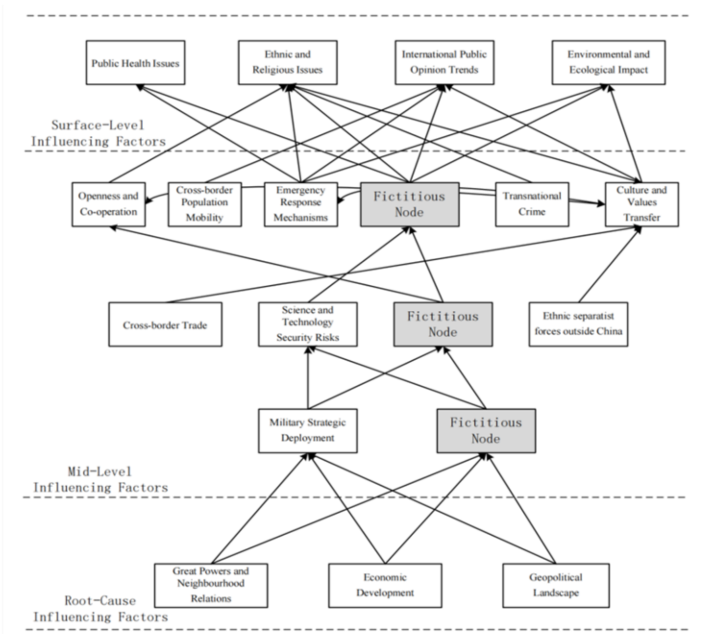

Figure.3. Multi-layer recursive structural model of foreign influences on public security in China's border areas

The first tier of influencing factors includes X12 (ethnic and religious issues), X11 (public health issues), X13 (international public opinion trends), and X15 (environmental and ecological impacts). These surface-level factors have a direct influence on public security in border areas. Adopting appropriate policies can effectively maintain security, and often quickly draws the attention of the party and government as well as the people.

The second tier of influencing factors covers nine mid-level factors from L2-L4, including X1 (openness and co-operation with the outside world), X2 (cross-border population movement), X4 (emergency response and co-ordination mechanism), X9 (transnational cross-border crime), X10 (culture and value transmission), X3 (cross-border trade exchanges), X5 (scientific and technological security risks), X16 (ethnic separatist forces outside the country), and X14 (military strategic deployment) . They act as linkages between surface and root factors and affect system stability.

Considering these factors helps to formulate policies, optimise resource allocation and enhance public security.

The third tier of influencing factors includes the three root factors of L5, namely X6 (great power and neighbourhood relations), X7 (level of economic development), and X8 (geopolitical pattern). These factors have a fundamental influence on the intermediate and surface factors and are key to the stability of the system. Based on the analysis of these factors, the foreign-related factors affecting public security in border areas can be fully understood.

5. Analysis of results

5.1 Factor correlation analysis

Firstly, among the surface-level influencing factors, some exhibit strong proactivity and are less constrained by other factors, while others are significantly influenced by factors at other levels. For example, in the case of Ethnic and Religious Issues (X12), the close connection between China's ethnic characteristics and religious beliefs creates a highly complex situation. If not properly coordinated, these issues may not only exacerbate social conflicts but also be exploited by external forces, thereby posing a threat to national security. It interacts with the intermediate-level factor Culture and Values Transfer (X10), where the impact of external cultures and values may further complicate ethnic and religious issues. Public Health Issues (X11) not only threaten the life and health of the people but can also cause panic and disorder, having a significant negative impact on social order and economic development. Under the backdrop of globalization, these issues pose a severe challenge to human health.Secondly, regarding International Public Opinion Trends (X13), some countries and organizations may, for political purposes, disseminate false information or biased reports through media and social platforms. These reports can mislead the public, exacerbate social conflicts, and even be used as tools to interfere in China's internal affairs. Lastly, Environmental and Ecological Impact (X15) is multifaceted. It not only threatens ecological balance and biodiversity but also poses long-term health hazards to residents. Additionally, in terms of emergency coordination management among nations, this issue may lead to some diplomatic disputes.

Secondly, intermediate-level influencing factors are interconnected with factors at other levels. Openness and Co-operation (X1) promotes regional economic integration and cultural exchange, facilitating resource sharing and market expansion. However, it may also introduce external risks and increase the complexity of security supervision. It also affects the surface-level factor International Public Opinion Trends (X13), as the outcomes and challenges of openness and cooperation can both become focal points of international attention. Cross-border Population Mobility (X2) and Culture and Values Transfer (X10) interact with each other. Cross-border population movement can to some extent promote cultural exchange and enhance the openness and inclusiveness of border areas. However, it may also be exploited by illegal elements to conduct illicit activities, posing potential threats to public security, social stability, and national security in border areas, and bringing negative impacts. An efficient Emergency Response Mechanism (X4) is crucial for enhancing the capacity of border areas to deal with emergencies, ensuring rapid and orderly emergency responses, and mitigating the adverse effects of emergencies on public security in border areas. Transnational Crime

(X9) may enable illegal individuals to take advantage of China's open policies to engage in illegal activities, endangering border security, social stability, and the health and well-being of the people, thus creating public security risks. Culture and Values Transfer (X10) is a key node. Conflicts in cultural identification are inherent and persistent, potentially impacting the lifestyle and mindset of local residents, weakening their identification with Chinese culture, leading to value conflicts, and affecting ethnic unity and social stability. Cross-border Trade (X3) can drive economic development but may also impact the stability of the domestic market. Moreover, technical trade barriers imposed by Western countries also pose a shock to the economic development of border areas. Science and Technology Security Risks (X5) are on the rise, including but not limited to key technology leakage, cyber-attacks, and the misuse of artificial intelligence. Ethnic Separatist Forces Outside China (X16) have become a tool in border public security that attempts to influence and split China. Especially after the end of the Cold War, ethnic separatism has become a main feature of the new wave of nationalism, leading to a resurgence of separatist ideologies in border ethnic regions, affecting social stability in regions such as Tibet and Xinjiang, and causing occasional violent and terrorist activities that are difficult to eradicate completely. Military Strategic Deployment (X14) has significant implications for political security. It can enhance the national defense capabilities of border areas and maintain regional security and stability through international military cooperation.

Finally, the root influencing factors are the foundation for social stability and long-term peace in the border areas. They not only exert direct or indirect influences on the intermediate and surface-level factors but also directly relate to the strategic overall situation of national sovereignty, security, and development interests. Great Powers and Neighbourhood Relations (X6), based on the theory of a “community with a shared future for neighbours” is extremely important for public security in border areas. The influence of Economic Development (X7) is multidimensional. It is essential to pay particular attention to the problem areas involved in the level of economic development and to take effective measures to promote the long-term stability and prosperity of border areas. Changes and conflicts in the Geopolitical Landscape (X8) have been continuously “tearing” the world apart over the past year. Shifts in the geopolitical landscape may exacerbate ethnic and religious issues in border areas, bring risks of transnational crime and illegal immigration, and thus pose challenges to border public security.

In summary, the influencing factors of border public security are interwoven and interact with each other, forming a complex system. The surface-level factors directly impact public security in border areas and are the immediate manifestations of the problems. The intermediate-level factors act like a bond, connecting the root factors with the surface-level factors and playing a crucial role in bridging the two. The root factors are the cornerstone of social stability and long-term peace in border areas, fundamentally influencing the stability of the entire public security system. These factors are interdependent and mutually restrictive, collectively shaping the complex landscape of border public security.

5.2 MICMAC Analysis

The rows and columns of the reachability matrix are summed to obtain the values of the driving force and dependency of each factor. The drive and dependency values of each factor were filled into the MICMAC analysis quadrant diagram as coordinates, and the average values of dependency and drive were used as the dividing line of the quadrant, and the results of the division are shown in Figure 4.

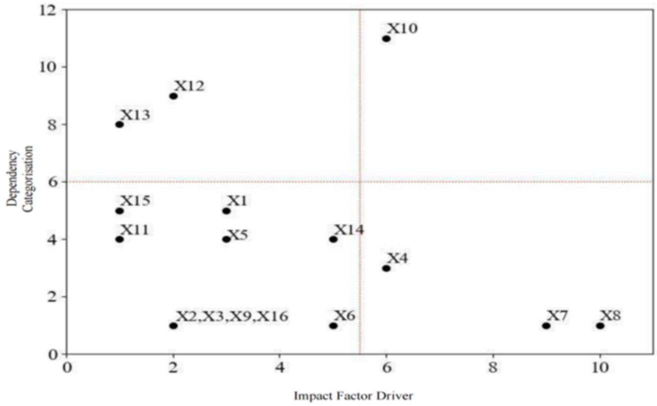

Figure.4. Impact Factor Driver-Dependency Categorisation Chart

The first quadrant is for spontaneous factors, which have low driving force and dependence and have a top-down function. It includes 10 factors such as X2 (cross-border population movement), which are not easily influenced by the system, have high stability, and are the cornerstone of the whole system. The second quadrant is the independent type of factors. Factors within this quadrant have high driving force and low dependency, are relatively less affected by other factors and continue to influence the whole system. Three factors, including X4 (Emergency Response Synergy Mechanism), are included in this region. The third quadrant is the linkage-type factors, with high factor drivers and dependencies within this quadrant, which contains factors such as X10 (Culture and Values Conveyance). Borderlands often have a complex cultural ecology of multi-ethnicity, multi-language and multi-religion, and their cultural ties with neighbouring countries or cross-border communities may pose a challenge. The fourth quadrant is Dependency, where factors with low drive and high dependency are usually at the top of the hierarchical chart, with X12 (Ethnic and Religious Issues) and X13 (International Public Opinion Trends), which are susceptible to change due to external influences.

6. Collaborative Governance Strategies for Border Security

This paper constructs a model of influencing factors for public security in border areas, composed of 16 factors, revealing the complex interrelationships among them, as shown in Figure 5. Based on this, the following governance strategies are proposed:

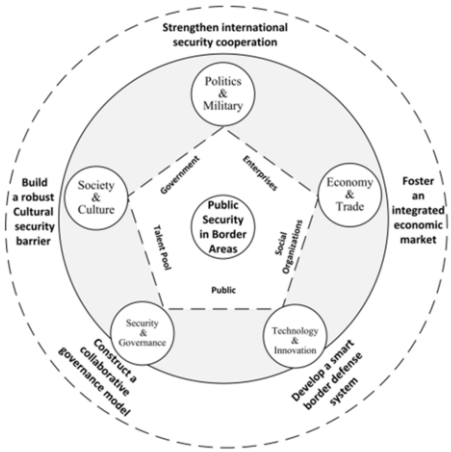

Figure.5. Path to realising the diversified construction of public security in the border areas

First, enhance international security cooperation to promote the building of a community with a shared future for mankind. By leveraging the in-depth implementation of the Belt and Road Initiative, efforts should be made to promote economic and social prosperity in border areas, strengthen counter-terrorism cooperation, combat transnational crime, and maintain cyber security. These actions will drive regional economic cooperation and cultural exchange.

Second, actively integrate into economic globalization to build a win-win market environment. Economic growth is essential for social stability[35]. It is necessary to continuously develop an open economy and strengthen cooperation with international organizations. In terms of trade, the import structure should be optimized by expanding the import of advanced technology, key equipment, and energy resources to enhance industrial competitiveness. Meanwhile, innovative models such as cross-border e-commerce and border resident trade can reduce trade frictions and protectionism risks, and improve cross-border trade management capabilities.

Third, guard against cultural penetration and fortify the cultural security frontier in border areas. In the face of ideological offensives from the West, it is crucial to deeply grasp the public opinion frontiers in border areas and utilize their role as a “super weapon” for leading social opinion and political socialization[36]. Therefore, the government should conduct public education and publicity to enhance public awareness of public security, guide the development of national culture, and encourage cultural industry innovation.

Fourth, construct a new model of border public security governance from a collaborative perspective. The cross-departmental collaborative governance model has significant advantages in reducing governance costs, improving government services, and enhancing residents' quality of life[37]. In the process of promoting collaborative governance in border areas, it is essential to accurately grasp and properly coordinate the relationship between the government, market, and society, building a governance model where all parties closely cooperate and work together. Additionally, leveraging technological means can achieve intelligent, refined, and efficient resource allocation, enhancing the effectiveness of collaborative governance.

Fifth, build a digital age border security barrier and promote the construction of a smart border. By enhancing digital technology capabilities and improving infrastructure in border areas, the digital divide in these regions can be narrowed to some extent. Leveraging digital intelligence in the public security system, utilizing big data analysis and artificial intelligence technology to predict environmental risks, and providing a scientific basis for decision-making can enhance the grassroots smart governance capabilities of border public security.

7. Conclusion

The marginal contribution of this study lies in its in-depth analysis of the foreign-related influencing factors of public security in border areas, guided by the overall national security concept and employing both qualitative and quantitative research methods. The study has revealed the complex interrelationships among these factors and proposed targeted governance strategies.

Despite the achievements, there are still limitations. Future research needs to further explore the specific mechanisms by which external factors influence internal ones, delve deeper into the interactions among the influencing factors of border public security, and construct collaborative mechanisms between border areas and surrounding regions, both domestically and internationally. It is hoped that this will provide a more scientific reference for border public security and put forward feasible strategies and innovative ideas.

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The Exploration of AI-Empowered Industrial Product Quality and Safety Supervision Pathways in the Context of Big Data

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Abstract. The widespread application of artificial intelligence (AI) technology has brought new solutions to the field of industrial product quality and safety supervision. This paper aims to delve into the effective pathways of AI-empowered industrial product quality and safety supervision in the context of big data, with the goal of enhancing supervisory efficiency. By comprehensively analyzing the existing problems and challenges in current industrial product quality and safety supervision work, this paper elaborates on the development status of big data and AI technologies and their potential application value in the supervisory field. It systematically investigates how to deeply integrate big data and AI technologies into every aspect of industrial product quality and safety supervision. By constructing a four-layer technical architecture for the supervision system—comprising perception, data, interaction, and application layers—this research promotes cross-departmental, multi-level governance system innovation. Building upon optimized resource allocation, it enhances the precision and foresight of industrial product quality and safety supervision work, facilitating overall improvement in regulatory practices.

Keywords. Artificial intelligence, quality and safety supervision, big data, digital transformation

1. Introduction

Industrial product quality and safety serve as crucial cornerstones for economic development and key safeguards for people's livelihoods. Traditional product quality supervision methods face numerous challenges when dealing with massive amounts of data and complex scenarios. In terms of supervision scope, as industrial product categories become increasingly diverse and production processes more intricate, it becomes difficult to comprehensively expand regulatory coverage, leading to potential regulatory gaps. Regarding supervisory efficiency, traditional approaches such as sampling inspections, on-site examinations, and special rectifications are time-consuming and labor-intensive, making it challenging to achieve real-time monitoring and dynamic management. Consequently, it becomes difficult to promptly identify and address product quality and safety issues. In terms of supervisory accuracy, the lack of

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effective collection and analysis of product lifecycle data makes it difficult to accurately grasp the overall status and potential risks of product quality, hindering the implementation of precise policy measures and targeted supervision.[1] These challenges urgently require new technological means and methods to be addressed.

The rapid development of big data and artificial intelligence technologies has brought new opportunities to industrial product quality and safety supervision. This paper aims to explore innovative pathways for artificial intelligence-empowered industrial product quality and safety supervision, with the anticipation of enhancing regulatory efficiency and effectiveness through technological means, ensuring product quality safety, and promoting healthy and sustainable industrial development. Big data technology can uncover potential risks in product quality by analyzing and mining vast amounts of data. As an important tool for big data analysis, artificial intelligence significantly improves regulatory precision and efficiency through its applications in pattern recognition, decision support, and other domains.

2. Current Status and Issues of Industrial Product Quality and Safety Supervision

2.1. Current Status of Industrial Product Quality and Safety Supervision

In recent years, China has maintained an overall stable work safety situation, with steady improvements in industrial product quality and safety standards. There have been no industry-wide, regional, or systemic quality and safety incidents. Between 2019 and 2024, market supervision authorities conducted quality supervision spot checks on over 14.6 million batches of products from more than 1 million enterprises, with a non-conformance rate of approximately 9%. Notably, non-conformance rates for health-related indicators consistently hovered around 4%. However, compared with the people's aspirations for a better life and the requirements of high-quality national economic and social development, there remains a gap in product quality and safety standards. Various scholars have proposed different solutions to enhance government regulatory efficiency from diverse perspectives. For instance, some scholars advocate promoting the transformation of government functions, clarifying jurisdictional boundaries of regulatory departments, and improving inter-departmental collaboration within government agencies.[2] Others suggest introducing multi-stakeholder oversight entities to expand participation in the legal governance model of product quality supervision, ensuring oversight effectiveness even when certain supervisory entities are absent.[3] Additionally, scholars propose innovating and optimizing regulatory methods, such as establishing a new credit-based market supervision mechanism, to improve regulatory efficiency. Nevertheless, no existing research has yet explored the enhancement of industrial product quality and safety supervision efficiency from the perspective of artificial intelligence empowerment.

2.2. Issues Faced by Supervisory Work in the Context of Big Data

- The depth and breadth of supervisory information and data collection are insufficient, with prominent issues of information asymmetry and lag. Information asymmetry places regulatory departments and enterprises in an unequal position. Due to limitations in technology, costs, privacy, and other aspects, it is difficult for regulatory departments to comprehensively obtain information about the entire process, including raw material procurement, production and processing, inspection and testing, and sales and distribution.[4] This asymmetry and lag can easily trigger opportunistic behavior by enterprises, resulting in limited accuracy in enterprise and product profiles, and further rendering regulatory work passive. If regulatory departments formulate policies and measures based on inaccurate or outdated information, they may not effectively solve practical problems and may even produce the opposite effect, which is not conducive to maintaining market order and ensuring product quality and safety.

- The increasing variety of industrial products and the continuous expansion of production scales have made big data processing a challenge for product quality and safety supervision, requiring powerful computing capabilities and efficient algorithms.[5] Facing massive amounts of data, traditional processing methods and tools struggle to complete data cleaning, integration, and analysis within a short time, making it difficult to promptly identify valuable information and potential risks in the data. As a result, regulatory decisions lack data support and struggle to be scientific and precise.[6] Data security and privacy protection are also significant challenges that the supervisory system must face in the era of big data. With the increasing volume of data, ensuring the secure storage, transmission, and access of data, as well as preventing data breaches and misuse, are important challenges that the supervisory system must address.
- Cross-departmental and cross-industry data sharing mechanisms have not yet been fully established. In the application of big data, data sharing and exchange among multiple departments and industries are required. However, due to the existence of information silos, there are obstacles to information exchange, making it difficult for regulators to promptly grasp the situation of enterprises and unify regulatory and enforcement efforts. This results in a disconnection between daily supervision and enforcement, leaving enterprises at a loss when cooperating with regulation.[7] The legal and regulatory framework for the supervisory system also needs further improvement. The current legal and regulatory framework has not yet fully adapted to the requirements of the big data era, which to a certain extent affects the application and development of big data technology in the field of product quality supervision.[8]

3. Technical Architecture Design of Industrial Product Quality and Safety Supervision System

When building an industrial product quality and safety regulatory system based on big data and artificial intelligence, the technical architecture design must fully consider intelligent requirements. The overall system should adopt a layered architecture, which can be divided from bottom to top into the perception layer, data layer, interaction layer, and application layer. Technical Architecture of Industrial Product Quality and Safety Regulatory System is shown in Figure 1. As the foundation of the system, the perception layer includes hardware resources such as servers, storage devices, and network equipment, as well as software environments such as operating systems and database management systems, providing stable and reliable operational support for the upper layers.[9] The data layer is responsible for data storage and management. A distributed storage system should be constructed to meet the storage needs of massive industrial product quality and safety data. By utilizing data warehousing techniques, data from different sources is cleaned, transformed, and integrated to form a unified data format and standard, providing high-quality data sources for subsequent analysis. The interaction layer serves as a bridge connecting the data layer and the application layer, providing services such as data processing, analysis, and mining. By introducing artificial intelligence algorithms such as machine learning and deep learning, functions such as product quality risk prediction and hazard identification are realized. Utilizing cloud computing platforms provides elastic scalability for services, ensuring stable system operation even in high-concurrency scenarios. The application layer is user-oriented, providing a friendly operating interface and rich application functions. It includes modules such as industrial product quality and safety status, industrial product risk warning, and decision-making support suggestions, allowing users to view product quality and safety status in real-time and handle abnormalities promptly. The system should also have good scalability, facilitating the introduction of new functional modules and technologies in the future.

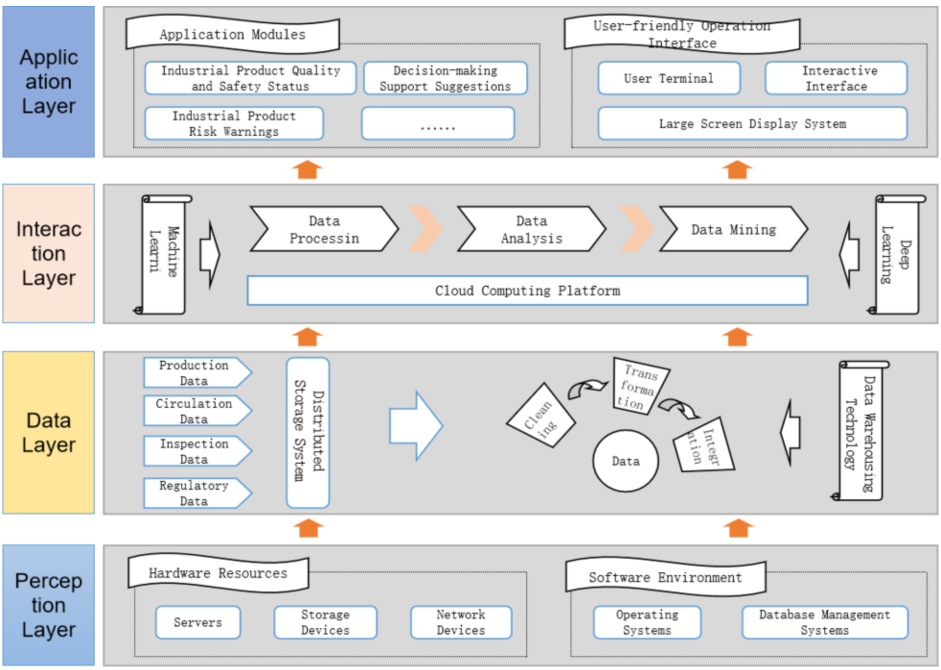

Figure 1. Technical Architecture Diagram of Industrial Product Quality and Safety Regulatory System.

4. Building a Regulatory System Driven by Big Data and Artificial Intelligence

4.1. Establishment of Data Sharing and Interaction Mechanisms

Establishing effective data sharing and interaction mechanisms is crucial for realizing the interconnection and interoperability of industrial product quality and safety regulatory information. At the national level, it is necessary to build a unified data sharing platform that adheres to open standards. This platform should extensively gather data resources from various channels, including regulatory information from government departments, internal business data from enterprises, and publicly available external market information. It is essential to formulate comprehensive data sharing and interaction standards. These standards should clearly define data formats, coding rules, interface specifications, etc., to ensure seamless integration between different systems. The standards should cover all aspects of data collection, transmission, storage, and processing, guaranteeing the accuracy and consistency of data during sharing and interaction. Incentive mechanisms for data sharing and interaction should be established. Enterprises should be encouraged to actively participate in data sharing, and those providing high-quality data should be given certain policy incentives or rewards, such as appropriate exemptions in regulatory inspections. At the same time, the rights and obligations of all parties involved in data sharing should be clearly defined to protect the legitimate rights and interests of data providers. During data sharing and exchange, security measures such as data encryption and access control should be strengthened to prevent data breaches and illegal use. Data audit mechanisms should be established to record data access and usage, ensuring the traceability of data usage.

4.2. Integration of Multi-source Heterogeneous Data Resources

Industrial product quality and safety regulatory involves a wide range of data sources and diverse types, and integrating multi-source heterogeneous data resources is of great significance for improving regulatory effectiveness. By utilizing big data technologies such as data cleaning, data integration, and data warehousing, fragmented, multi-source data can be effectively integrated. Artificial intelligence technologies are then used to perform in-depth mining on the integrated data. By establishing data mapping rules, setting deduplication rules, utilizing distributed storage and computing technologies, and employing big data processing frameworks such as Hadoop and Spark, massive amounts of data can be efficiently processed and analyzed. This allows for the extraction and identification of potential risk patterns and trends, providing a scientific basis for industrial product quality and safety regulatory. By learning patterns and trends in historical data, product quality risk points can be automatically identified, enabling rapid response and early warning to abnormal situations. Deep learning technologies are used to integrate information across departments and systems, improving the depth and accuracy of data processing. This helps regulatory departments to more accurately identify issues, allowing regulatory measures to be more precisely targeted at specific problems, reducing unnecessary interventions on innocent enterprises, and avoiding waste of resources. Data access control mechanisms are established to control the scope of data access based on user roles and permissions, preventing unauthorized access and use of data. Algorithms are continuously learned and optimized to enable artificial intelligence systems to continuously improve the accuracy and efficiency of data analysis, while also adjusting regulatory strategies based on new data changes to ensure that regulatory measures keep pace with the times.

4.3. Deployment and Optimization of Artificial Intelligence Models

In the industrial product quality and safety regulatory system, the deployment and optimization of artificial intelligence models are of crucial importance. In terms of model deployment, it is first necessary to select an appropriate model deployment environment based on the actual needs of the regulatory system. For scenarios with high real-time requirements, models can be deployed on edge computing devices to enable real-time analysis and processing of data. For example, during the approval process for industrial product production licenses, AI models can rapidly review application materials submitted by enterprises, assisting supervisors in improving approval efficiency. For scenarios with large amounts of data and complex calculations, cloud computing platforms can be chosen for deployment, leveraging the powerful computing capabilities for management and decision-making. For instance, AI models can analyze historical data to predict potential quality issues and safety risks, enabling early warning and intervention. Deploying data collection at the enterprise level captures production process data, while utilizing convolutional neural networks (CNNs) to identify product surface defects, packaging integrity, and other factors, helping enterprises enhance product quality. By continuously monitoring the model's operating status and performance indicators in real-time, the effective operation of the model can be continuously monitored, and issues during model operation can be promptly identified. New regulatory-related data is continuously collected to train the model, promoting continuous updates and optimization of the model. Model fusion techniques are used to obtain more accurate prediction results, combining different types of models such as random forests and support vector machines to improve the overall performance of the model. Parameter optimization methods such as grid search and random search are used to adjust and optimize the model's hyperparameters, such as the learning rate and regularization coefficients, to achieve optimal performance on specific tasks and enhance the model's effectiveness.

5. Guarantee Measures for the Application of Artificial Intelligence in Industrial Product Quality and Safety Regulatory

5.1. Creating a Favorable Policy and Institutional Environment

Competent departments in the artificial intelligence industry must play the role of system designers and resource allocators by drawing on the experience of the EU's Artificial Intelligence Act, which incorporates regulatory sandbox mechanisms into AI governance frameworks. They should take the lead in formulating exclusive laws and regulations for artificial intelligence. These laws should clarify the responsibilities and obligations of government departments, research and maintenance institutions, and users, and specifically address legal or ethical issues such as data security, privacy protection, technology misuse, and algorithmic discrimination that arise in the context of the widespread application of artificial intelligence. When constructing a regulatory system based on artificial intelligence technology, market regulatory departments should prioritize requirements for algorithmic transparency and explainability to avoid algorithmic "black boxes". They should also develop technical specifications for the use of artificial intelligence, strictly regulating the development, use, and management of artificial intelligence models, and providing guidance to regulatory personnel on their proper use to ensure the lawful and compliant application of new technologies in regulation. At the same time, it is necessary to strengthen public opinion dissemination to enhance society's positive awareness of industrial product quality and safety regulatory work empowered by artificial intelligence, reduce ethical disputes arising from the application of artificial intelligence-related technologies, and promote linkage and synergy between government regulation and social oversight.

5.2. Exploring Talent Cultivation and Utilization Mechanisms

The promotion and application of artificial intelligence technology will inevitably have a profound impact on the structure of the talent market. The regulatory system requires a large number of technical talents with relevant knowledge and skills for system development, maintenance, and optimization, as well as data analysis and utilization. To address the issue of technical talent shortages, it is necessary to develop comprehensive talent cultivation strategies. On the one hand, it is important to strengthen cooperation with universities and research institutions, establish relevant majors and courses based on the characteristics of industrial product quality and safety regulatory work, and cultivate a large number of professionals with knowledge in big data, artificial intelligence, etc. On the other hand, it is necessary to provide training for existing regulatory personnel, expand the development space for different types of talent to move up and down, and increase opportunities for in-service learning and training and academic qualifications. By adopting methods such as sharing of achievements, mutual recognition of credits, and collaborative research on algorithms, we can break down the invisible barriers and field gaps between higher education, vocational education, lifelong learning, and self-directed learning. Additionally, methods such as "peer review", "anonymous review", and "self-recommendation" can be used as important supplements to "organizational evaluations".

5.3. Multi-stakeholder Governance to Form Synergy

It is necessary to pool the strengths of all sectors of society, establish a high-tech talent alliance and an innovation resource-sharing platform led by the government, supported by enterprises, and involving social participation, give full play to the decisive role of the market in resource allocation, and continuously activate enterprises' internal motivation and innovative vitality to extensively utilize artificial intelligence-related technologies. We should actively promote the construction of an open-source ecosystem, lower the threshold for the application of artificial intelligence technologies in various industries, guide various types of capital to invest in the "source" of innovation, open up more opportunities for public recruitment for tasks such as architecture design, model optimization, and code writing, and explore new models of cross-border cooperation. With an open attitude and international perspective, we should form in-depth collaboration with developed countries and major economies in basic research, technology development, and standard setting, and promote the normalization and standardization of general artificial intelligence technologies on an international scale.

6. Conclusion

In the wave of rapid development of big data and artificial intelligence technologies, their application prospects in the field of industrial product quality and safety regulatory are vast. Research shows that digital technologies such as artificial intelligence, with their efficiency, intelligence, and global optimization capabilities, can enhance the accuracy of industrial product quality and safety regulatory work and promote the overall improvement of regulatory work by strengthening policy coordination and promoting cross-departmental and multi-level governance system innovation on the basis of optimizing resource allocation. It should be noted that this article is only a preliminary exploratory theoretical study, and in the future, it will be necessary to conduct in-depth research by combining theory with practice and seeking breakthroughs in development from three aspects: technology, policy, and system. At the technical level, it is necessary to continue to optimize artificial intelligence technologies such as machine learning and deep learning and continuously improve the accuracy and efficiency of models. At the policy level, it is necessary to formulate relevant laws and regulations to provide clearer legal guidance and guarantees for the application of new technologies and regulate market order. At the institutional level, it is necessary to promote the integration and utilization of data resources across the entire industry and overcome the limitations of traditional regulatory work.

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Artificial Intelligence-Empowered Water Resources Management: A CiteSpace-Based Scientometric Review

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Abstract. With the advancement of information technology, artificial intelligence-empowered water resources management has emerged as a critical research frontier in the water conservancy sector. Utilizing CiteSpace visualization software, this study constructs knowledge maps to systematically analyze the research landscape of artificial intelligence applications in water resources management through four dimensions: annual publication output, scholarly author analytics, country/institution research profiling, and keyword co-occurrence networks. Further investigations via clustering analysis and burst detection reveal hotspot themes and evolutionary trajectories in AI-driven water governance. These methodologies provide a comprehensive and objective understanding of the field's developmental dynamics, while identifying existing research gaps.

Keywords. Artificial intelligence, Water resources management, Visualization analysis, Research hotspots

1. Introduction

Water resources management refers to the organization, coordination, supervision, and dispatching of water resources development, utilization, conservation, and protection [1]. With the accelerated development of artificial intelligence technology and the rapid advancement of water conservancy informatization, the water sector will encounter the big data and artificial intelligence (AI) revolution, the fourth revolution [2]. The application of artificial intelligence in the field of water resources management has attracted widespread attention and has gradually become a research hotspot. To holistically assess the trends of AI-empowered water resources management, this study employs CiteSpace 6.3.R1—a specialized bibliometric analysis software—to generate

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knowledge maps that systematically visualize the research landscape and hotspot themes within this domain.

2. Data Sources and Research Methods

2.1. Data Sources

To ensure the efficiency of sample data, this study used the search function of Web of Science, limited the source of literature data to "Web of Science Core Collection". The subject was set to "artificial intelligence" and "water resources management". The document type was set to "article" and "review Article". The source category was set to SCI-EXPANDED and SSCI. And the search date was set from 2010 to 2025. Finally, 520 documents were retrieved. The downloaded documents were imported into CiteSpace 6.3.R1 for format conversion, and 520 sets of valid data were obtained.

2.2. Research Methods

This study used the visualization analysis software CiteSpace 6.3.R1 to construct a series of scientific knowledge maps to form an analysis of the potential driving mechanism of disciplinary evolution and explore the frontiers of disciplinary development [3]. CiteSpace 6.3.R1 was run to establish a project, and the specific parameters were set as follows: the time period was divided into 2010-2025, and the time slice was 1 year; the node types were adjusted to author, institution, and keyword respectively. In the node screening module, a threshold of k=15 was applied to retain the top 15 nodes based on citation frequency. These selected nodes were then used to calculate the g-index, ensuring a focus on the most influential publications. To reconcile global network parsimony with localized temporal fidelity, this study set the visualization module to "cluster view-static" and "show merged pruning", and the pruning module to "pathfinder" and "pruning sliced networks".

3. Research Overview Analysis

3.1. Temporal Publication Trend Analysis

As shown in Figure 1, the number of publications focusing on the topics of "artificial intelligence" and "water resources management" increased significantly after 2019, reaching its peak of 114 papers in 2024. Based on the growth curve of annual publications, it can be speculated that the growth trend will continue in 2025 and beyond.

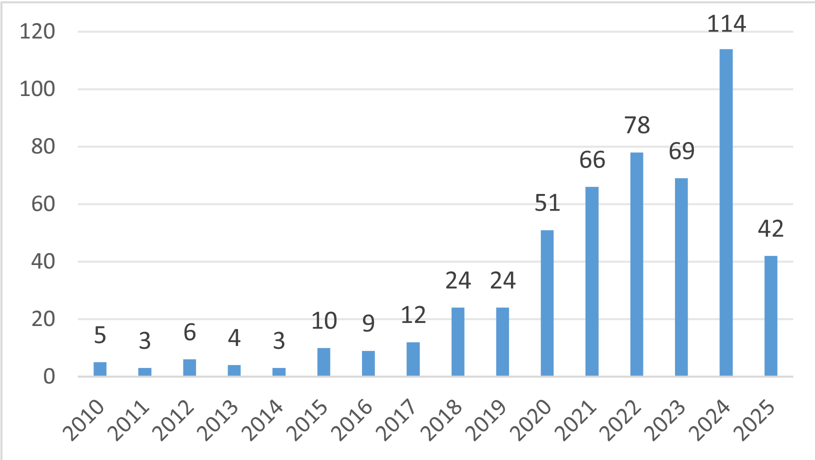

Figure 1. The publication status of papers from 2010 to 2025

3.2. *Scholarly Author Analytics*

The co-occurrence map of author collaboration directly reflects the high-yield authors in this research field and the collaboration between authors [3]. As shown in Figure 2, the number of nodes is 249 (N=249), the number of links is 298 (E=298), and the density of the association network between authors is only 0.0097 (density=0.0097). These statistics indicate that the degree of collaboration in this research field is relatively low. The authors with the largest number of papers in this field are Kisi Ozgur, Yaseen Zaher Mundher, and Aljundi Isam H, who have published 16, 13, and 9 papers, respectively.

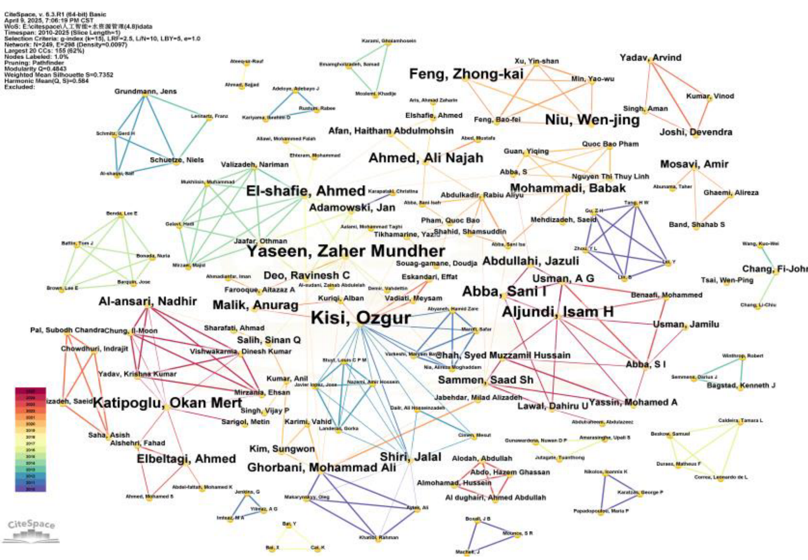

Figure 2. Author co-occurrence network

3.3. Country/Institution Research Profiling

The institutional co-occurrence collaboration network map constructed by CiteSpace 6.3.R1 software (as shown in Figure 3) shows that the number of nodes is 217 (N=217) and the number of connections is 306 (E=306). The network density between institutions is only 0.0131, and the color of the connection indicates the publication time. The network map indicates that the connection between institutions is not close enough, and the cooperation and communication are relatively lacking. In the future, artificial intelligence research in the field of water resources management must focus on strengthening cross-regional and multi-institutional collaborative research.

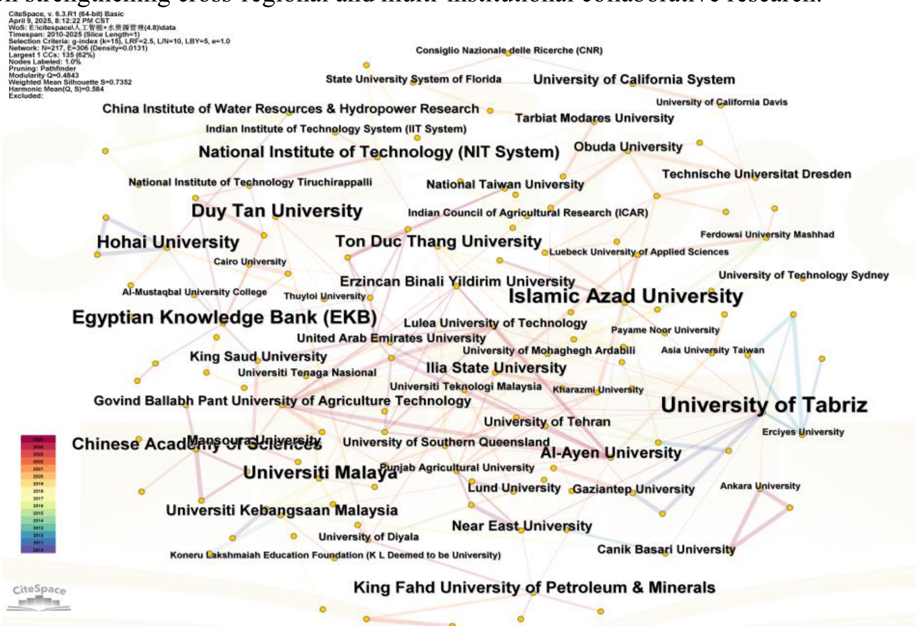

Figure 3. Institutional co-occurrence collaboration network

As shown in Table 1, the leading institutions in the field of artificial intelligence applications in water resources management, including University of Tabriz, Islamic Azad University, Egyptian Knowledge Bank (EKB), Duy Tan University, and Universiti Malaya, have each published 15 or more related papers.

Table 1. Top 5 insitutions in the field of artificial intelligence-empowered water resources management

Rank	Insitutions	Count	Year
1	University of Tabriz	30	2010
2	Islamic Azad University	24	2012
3	Egyptian Knowledge Bank (EKB)	18	2020
4	Duy Tan University	17	2020
5	Universiti Malaya	16	2016

As shown in Table 2, in the field of artificial intelligence in water resources management, Chinese scholars published the largest number of papers, a total of 117 papers. This accounts for 22.5% of the total number of papers published. Scholars from

Iran, India, the United States, and Saudi Arabia followed, publishing 116, 72, 69, and 48 papers, respectively. Among these five countries, Chinese and Iranian scholars were among the first to engage in research in this field.

Table 2. Top 5 countries in the field of artificial intelligence-empowered water resources management

Rank	Countries	Count	Year
1	PEOPLES R CHINA	117	2010
2	IRAN	116	2010
3	INDIA	72	2014
4	USA	69	2013
5	SAUDI ARABIA	48	2012

4. Visualization and Analysis of Hotspots and Trends

4.1. Keyword Co-occurrence Analysis

Keywords are used to express the research topic of the literature. As shown in Figure 4, the keyword co-occurrence map created with CiteSpace software can reflect the core content and hot topics in the field. The map shows 254 nodes (N=254) and 889 links (E=889), and the connection between keywords is relatively close. The size of the circular nodes in the map indicates the frequency of keyword occurrence. The higher the frequency, the larger the node size.

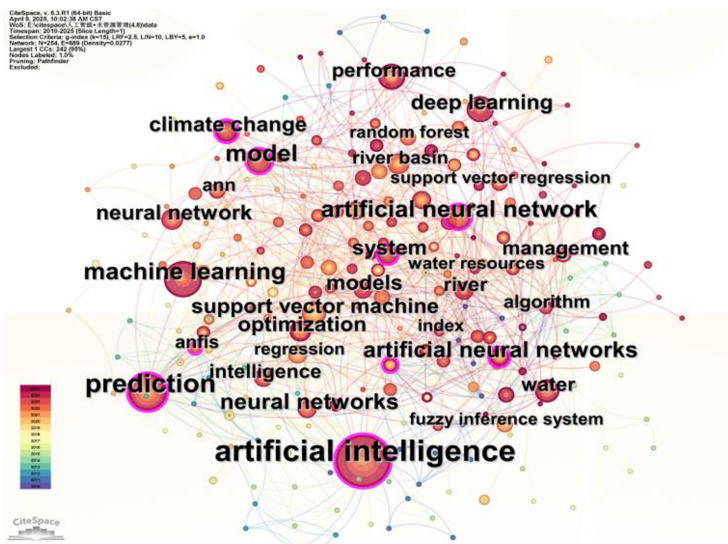

Figure 4. Keyword co-occurrence network

As shown in Table 3, according to the map data, the top five keywords with the highest frequency are counted to analyze the research hotspots in this field. The top five keywords in this research field are artificial intelligence, prediction, artificial neural network, machine learning, and model, which reflect the research hotspots.

Table 3. Top 5 high-frequency keywords

Rank	Count	Year	Keywords
1	192	2010	artificial intelligence
2	109	2011	prediction
3	69	2014	artificial neural network
4	68	2020	machine learning
5	58	2013	model

4.2. Keyword Clustering Analysis

The keyword clustering map provides a thematic perspective on the research hotspots in a specific field and reflects the research focus of that field. The module value (Q value) and average profile value (S value) of the cluster are the criteria for judging the effect of the keyword clustering map. The Q value and S value range from 0 to 1. When the Q value is greater than 0.3, it indicates that the clustering structure is significant; when the S value is greater than 0.5, it indicates that the clustering is reasonable; when the S value is greater than 0.7, it indicates that the clustering is efficient and convincing [3]. As shown in Figure 5, the keyword clustering map produced using CiteSpace 6.3.R1 shows that there are 254 keyword network nodes (N=254), 889 links between nodes (E=889), and the link density (Density) is 0.0277. The Q value is 0.4843, which is greater than 0.3, indicating a significant clustering structure; the S value is 0.7352, which is greater than 0.7 and close to 1, indicating efficient clustering.

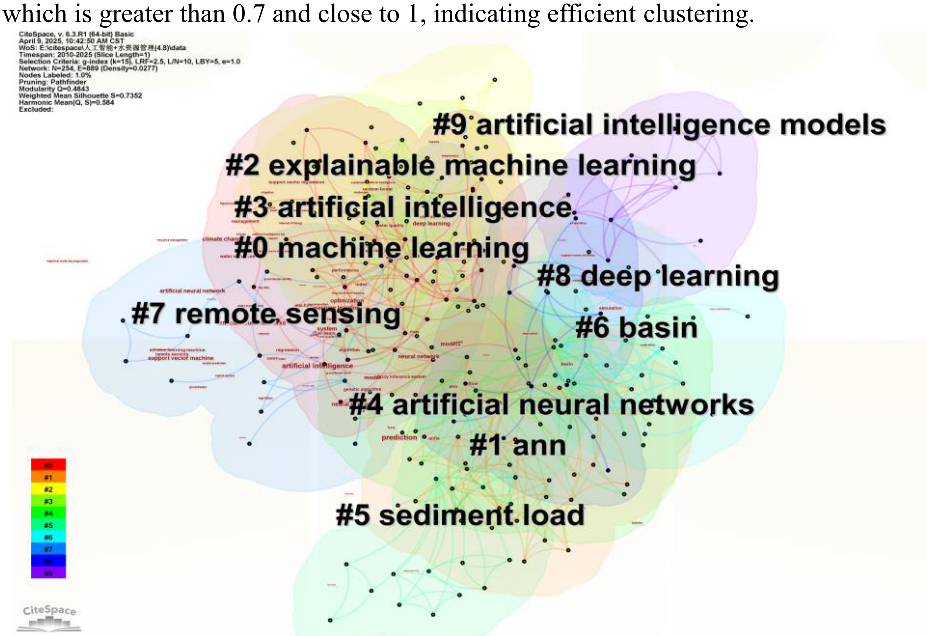

Figure 5. Keyword clustering visualization

The map shows 10 core clusters, namely machine learning (#0), ANN (artificial neural networks) (#1), explainable machine learning (#2), artificial intelligence (#3), artificial neural networks (#4), sediment load (#5), basin (#6), remote sensing (#7), deep learning (#8), and artificial intelligence models (#9). The relevant information (size, silhouette and top terms) of the 10 clusters is presented in Table 4, which analyzes the distribution of key topics in the research hotspots. Taking machine learning (#0) as an example, the cluster has 36 nodes; the silhouette value is 0.787; the cluster labels include machine learning, hybrid model, big data, ensemble learning, and groundwater vulnerability (LLR[log-likelihood ratio] algorithm); the average publication year of the citations is 2020. This shows that in the field of artificial intelligence applied to water resources management, research on machine learning is closely related to or appears with the keywords machine learning, hybrid model, big data, ensemble learning, and groundwater vulnerability.

Table 4. Top 10 keywords clustering

Cluster	Size	Sihouette	mean(Year)	Top terms(LLR)
machine learning	36	0.787	2020	machine learning; hybrid model ; big data; ensemble learning ; groundwater vulnerability
ann	33	0.684	2016	ann; deep learning; soft computing ; machine learning; suspended sediment yield
explainable machine learning	28	0.604	2021	explainable machine learning; random forest ; support vector regression; temperature; calibration period
artificial intelligence	28	0.817	2017	artificial intelligence (ai) ; industrial energy efficiency; industrial sustainability; industry 4.0; operational performance
artificial neural networks	24	0.669	2016	artificial neural networks ; extreme learning machine; model ; artificial intelligence ; gms
sediment load	22	0.819	2014	artificial intelligence ; sediment load ; groundwater level ; water demand ; hybrid model
basin	20	0.757	2014	basin; genetic algorithm; surrogate model; mahanadi river ; water discharge
remote sensing	19	0.706	2020	remote sensing; explainable artificial intelligence; google earth engine; artificial groundwater recharge; winter drawdown
deep learning	14	0.61	2018	deep learning; long short-term memory; neural networks ; support vector machines; warm-arid
artificial intelligence models	10	0.882	2013	artificial intelligence models; fao penman-monteith method ; outdoor recreation; long short-term memory network; crop water requirements

4.3. Keyword Burst Detection

Keyword emergence analysis helps to present the degree of sudden increase in research interest in a specific discipline and track the frontier dynamics and development trends in the research field [4]. Figure 6 shows the change status and trend of the keywords in the field of artificial intelligence-empowered water resources management over a specific period of time, such as appearance or disappearance, strengthening or weakening. By observing the time of keyword appearance and outbreak, we can identify shifts in research focus. From 2010 to 2020, flow, neural networks, ANFIS (adaptive neuro-fuzzy inference system), artificial neural networks, model, ANN, support vector machine, fuzzy inference system, regression, and area were hot topics; from 2020 to 2025, random forest, calibration, surface water, basin, remote sensing, and impact were hot topics.

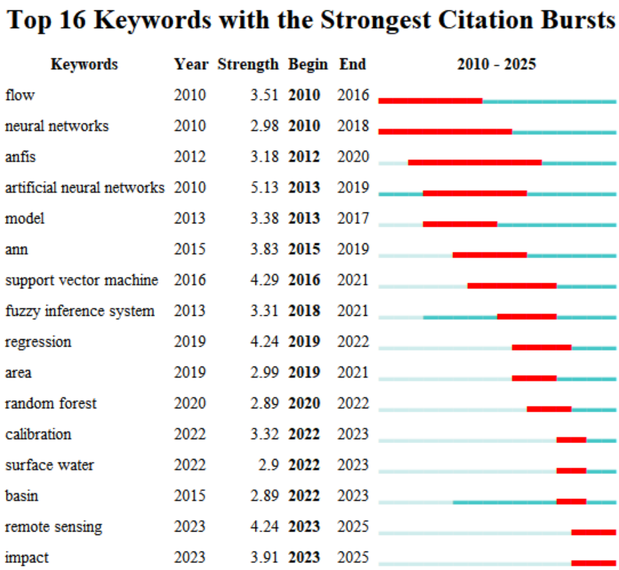

Figure 6. Top 16 keywords with the strongest citation bursts

5. Conclusions

In recent years, with the development of information technologies such as artificial intelligence, the water conservancy field has been undergoing profound changes. Artificial intelligence-empowered water resources management has gradually become an important issue in this field. This study uses CiteSpace software to construct a series of knowledge maps, presenting the research overview, hot topics, and development trends in the field of artificial intelligence-empowered water resources management.

The research overview of artificial intelligence-empowered water resources management is as follows: In terms of the number of publications, the annual number of publications continues to grow, with a significant increase starting in 2020 and reaching a peak in 2024. It is predicted that the number of publications in related research will continue to rise in the future. In terms of research strength, although the academic community has formed a local author cooperation network, it remains decentralized and individualized as a whole. Cooperation between research institutions is relatively scattered and lacking. The top five countries in terms of the number of publications in related fields are all countries with greater water resource pressure.

CiteSpace 6.3.R1 was used to construct keyword co-occurrence and cluster maps to present the research hotspots and development trends in the field of artificial intelligence-empowered water resources management. According to the maps, the top five hot topics in academic research are artificial intelligence, prediction, artificial neural network, machine learning, and model, The top ten clusters formed by the hot areas of sample literature are machine learning, ANN (artificial neural networks), explainable machine learning, artificial intelligence, artificial neural networks, sediment load, basin, remote sensing, deep learning, and artificial intelligence models.

The following explores the clusters using machine learning and ANN as examples. In terms of machine learning, Ahmed et al.(2024) explored the various ML (machine learning) techniques that have been applied within the realm of water resources management. These applications include groundwater management, water distribution systems, water quality and wastewater treatment, water demand and consumption, hydropower and marine energy, irrigation and agriculture, water drainage systems, and flood management and defence [5]. In terms of ANN, the model is widely applied in various regions, such as the Yangtze River Basin and Ningxia region of China, California in the United States, and Khuzestan Province in Iran, among others.

This paper conducts a bibliometric analysis utilizing CiteSpace, which enables us to gain insights into the research landscape and trends within the academic community in this particular field, thereby facilitating more informed and effective engagement in related research endeavors and decision-making processes.

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Remaining Life Prediction of Bearings Based on Self-Coding Feature Enhancement

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Abstract. Aiming at the problem of insufficient mining of bearing degradation information in the previous deep learning-based bearing remaining useful life (RUL) prediction, resulting in large deviation of life prediction performance, which makes it difficult to maintain the failed equipment in time to avoid potential safety hazards, this paper proposes a new end-to-end bearing RUL prediction method based on Self-Coding Feature Enhancement (SFENet). The method first implements feature extraction and enhancement with the help of a self-coding codec, then inputs the enhanced features into a multilayer Long Short-Term Memory (LSTM) network for temporal feature extraction, then develops RUL prediction through multiple fully-connected layers, and finally applies multiple Mean-Square Error (MSE) loss functions to complete the training. Experimental validation on the PHM2012 bearing dataset shows that the proposed self-coding feature enhancement method can effectively strengthen the features, and the proposed model achieves competitive results on the test bearings, and compared to the Dilated Casual Convolution Enhanced Transformer (DCCET) model, RMSE has decreased by 25.4%.

Keywords. Bearing life prediction, Self-coder, Feature enhancement, Temporal feature extraction

1. Introduction

In the service process of a naval gun, its stable operation is highly dependent on the coordinated cooperation of various mechanical equipment such as motors, gears, bearings, and screws. Accurate RUL prediction can predict potential equipment failures in advance, provide scientific basis for preventive maintenance, significantly improve the reliability and stability of mechanical equipment, and comprehensively enhance the autonomous support capability of a certain naval gun in complex combat environments. As an indispensable key component in these mechanical equipment, bearings have outstanding research value in RUL prediction [1-3].

We focus on the key component bearings in mechanical equipment and are fully exploring the RUL prediction method for bearings based on vibration signal analysis. The current research on RUL prediction in the industry is mainly divided into two directions: one is to construct a health indicator system carefully and use it as the basis for RUL prediction [4,5]; Another type is the end-to-end RUL prediction mode based on deep learning techniques [6,7]. Compared to the former, the end-to-end RUL prediction mode

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based on deep learning is widely praised and favored by researchers because it does not require prior knowledge constraints and can complete the prediction process solely through data-driven approaches. Early research often used CNNs [8-12], which automatically extracted fault features and constructed life prediction models by convolving the time-frequency images of bearing vibration signals. Its local perception and weight sharing mechanism significantly improved the efficiency of feature extraction. With the deepening of research, RNNs and their variants such as LSTM [13] and GRU have been widely applied. These models capture the time series characteristics of bearing operation data through memory units, effectively solving the problem of traditional methods being difficult to handle dynamically changing data. In addition, the introduction of attention mechanism and Transformer architecture further enhances the model's ability to focus on key features, enabling more accurate characterization of subtle changes in the degradation process of bearings. Although the above research effectively simplified the complex feature extraction process using deep learning methods and successfully excavated the deep essential features of vibration signals, it must be pointed out that when only using CNNs for feature extraction of the original bearing vibration signals, it is often difficult to fully explore the rich information contained in the bearing degradation process.

In view of this, in order to overcome the prominent problem of insufficient mining of bearing degradation information using only CNNs, this paper innovatively proposes a bearing remaining life prediction method based on Self-Coding Feature Enhancement. Firstly, taking the vibration signal of rolling bearings as the research object, a comprehensive and detailed feature extraction operation is carried out through a carefully designed custom coding CNN. After completing feature extraction, the data is split into two different branches for further processing. One branch utilizes custom decoding CNN to up-sample the extracted features, achieving accurate restoration of the original vibration signal and using it as the predicted value. The original input vibration signal is used as the label, and the mean square error loss function is used to continuously reduce the error between the predicted value and the actual label, while cleverly enhancing the extracted features. The other branch takes the enhanced features as input data and inputs them into a multi-layer LSTM for temporal feature extraction. Then, multiple fully connected layers are used for the final RUL prediction output. By using self-coding in the feature extraction stage, this method successfully achieves the goal of feature enhancement and greatly improves the overall accuracy level of RUL prediction.

2. Methodology

The SFENet model for predicting the remaining service life of bearings proposed in this paper adopts a multi branch fusion architecture, as shown in Figure 1. It mainly consists of three parts: a CNN based encoder, a transposed CNN based decoder, and a temporal feature extractor. The model first encodes and extracts features from the original vibration signal through a custom CNN backbone network, and then inputs the features into two parallel branches: in the reconstruction branch, transposed CNN is used for layer by layer up-sampling to reconstruct the original signal, and the reconstruction error is calculated through the mean square error loss function; In the life prediction branch, LSTM and fully connected layers are used to extract temporal features, and the remaining life is used as the supervised signal to calculate the prediction error. Ultimately, end-

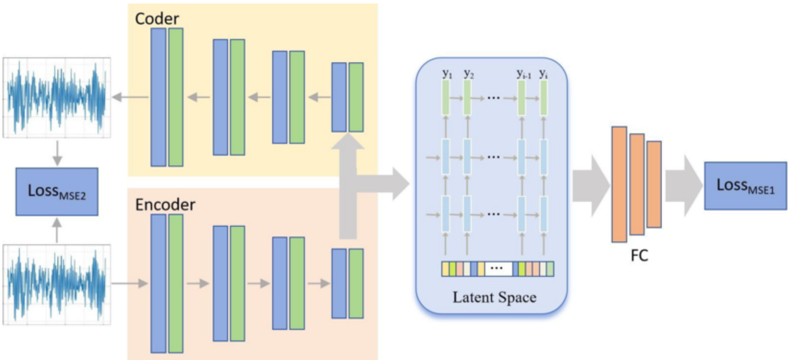

Figure 1. Overall architecture diagram of the SFENet for bearing RUL prediction.

to-end model training is achieved by jointly optimizing the loss functions of the two branches, effectively improving the accuracy of remaining life prediction.

2.1. *Self-coding feature enhancement*

In this paper, a self-coding feature enhancement method for bearing residual life prediction is proposed, which consists of three main components: a CNN-based encoder, a transposed CNN-based decoder, and a temporal feature extractor. In the study, a custom CNN is used as the backbone network to process a one-dimensional bearing vibration signal $X = (x_1, x_2, \ldots, x_T) = \{x_t|_1^T \in \mathbf{R}^T\}$ of length T, where x_t denotes the t-th vibration signal. input X_{freq} into the CNN based custom encoder $CNN_{encoder}$:

$$f = CNN_{\text{encoder}}(X) \in \mathbf{R}^{T'} \tag{1}$$

where f is the encoded result, which is also the result of feature extraction, and T's the length of the down-sampled sequence. Afterwards, f is input into two branches, and in the reconstruction branch, the input data is reconstructed through a custom decoder:

$$X' = CNN_{decoder}(f) \in \mathbf{R}^T \tag{2}$$

where X' is the reconstructed data, and the reconstruction error is calculated using the mean square error loss function with the input data.

In the life prediction branch, we input f into LSTM for sequence feature extraction:

$$f' = LSTM(f) \in \mathbf{R}^{T'} \tag{3}$$

where $f^{'}$ is the result of sequence feature extraction, and the sequence length remains unchanged. We only take the last output $f_{end}^{'}$ from $f^{'}$ as the input for the next fully connected layer $F_{linear}(\cdot)$:

$$f_{RUL_{predict}} = F_{linear}(f_{end}^{'}) \in \mathbf{R}^1 \tag{4}$$

where $f_{RUL_{predict}}$ is the final remaining life prediction value.

2.2. LSTM

The core of LSTM lies in three key gating units: forgetting gate, input gate, and output gate. Each of these gating structures employs a Sigmoid activation function (output range [0,1]) to dynamically regulate the information flow. Among them, the forgetting gate determines the retention level of historical information, the input gate controls the updating intensity of new information, and the output gate regulates the exposure level of the current state. This sophisticated gating mechanism enables the network to adaptively learn and maintain key temporal features in long sequences.

(1) The forgetting gate, which determines which information should be discarded from the cellular state, is given by the following equation.

$$f_t = \sigma\left(W_f\left[h_{t-1}, x_t\right] + b_f\right) \tag{5}$$

where f_t denotes the output of the oblivious gate, x_t is the input data, h_{t-1} is the hidden state at the previous moment, W_t is the weight matrix, and b_f is the bias term.

(2) The input gate, which determines which new information should be stored into the cell state, is given by the following equation:

$$i_t = \sigma\left(W_i\left[h_{t-1}, x_t\right] + b_i\right) \tag{6}$$

$$\tilde{c}_t = tanh\left(W_c\left[h_{t-1}, x_t\right] + b_c\right) \tag{7}$$

where i_t denotes the output of the input gate, $\tilde{c}_t$ is the candidate cell state, W_t and W_c are weight matrices, and b_i and b_c are bias terms.

Cell state update:

$$c_t = f_t * c_{t-1} + i_t * \tilde{c}_t \tag{8}$$

where c_t is the updated cell state and $*$ denotes element-level multiplication.

(3) The output gate, which determines which information should be output from the cell state, is given by the following equation:

$$o_t = \sigma\left(W_o\left[h_{t-1}, x_t\right] + b_o\right) \tag{9}$$

$$h_t = o_t * tanh(c_t) \tag{10}$$

where o_t denotes the output of the output gate, h_t is the hidden state at the current moment, W_o is the weight matrix, and b_o is the bias term.

2.3. Joint loss function

The MSE loss function serves as the underlying optimization objective of the model, which ensures a high degree of consistency between the predicted values and the true labels at the numerical level by minimizing the squared error between the two. This design not only motivates the encoder-decoder structure to effectively capture the essential features of the signal through self-supervised learning, but also provides a more discriminative representation for the temporal feature extraction module, thus significantly improving the accuracy and robustness of the remaining lifetime prediction task.

$$MSE(y,y') = \frac{\sum_{i=1}^{n}(y_i - y'_i)^2}{n} \tag{11}$$

where n is the number of data, y_i is the objective value of the i-th data, and $y_i^{'}$ is the predicted value of the i-th of the model, so minimizing this function is the goal of optimization.

In this paper, the model adopts the joint optimization strategy of dual loss functions: firstly, based on the difference between the reconstructed output of the decoder and the original input signal, a self-supervised loss function L_{MSE_1} is constructed; secondly, based on the error between the final prediction value of the model and the actual residual life of the bearings, a supervised loss function L_{MSE_2} is constructed. Through linear combination of these two MSE loss functions, the overall optimization goal of the model is formed, which is expressed by the mathematical expression as follows:

$$L_{Mix} = \alpha L_{MSE_1} + \beta L_{\mathrm{MSE}_2} \tag{12}$$

where α and β are two hyperparameters, and the weights of the two MES losses in the mixing loss are changed by varying the values of these two hyperparameters. This joint optimization mechanism ensures both the characterization ability of feature learning and the accuracy of lifetime prediction.

2.4. Model parameter

The SFENet model adopts a multi module collaborative architecture design, mainly composed of three modules. The encoder based on CNN transforms the original high-dimensional vibration signal into a feature representation with rich semantic information. The decoder based on transposed CNN achieves feature to original signal space reconstruction through deconvolution in the signal reconstruction branch. In the life prediction branch, the temporal feature extraction module captures the temporal dependencies during the bearing degradation process through an LSTM network, and combines a fully connected layer to achieve nonlinear mapping from temporal features to remaining life values. The detailed network structure and parameter configuration are shown in Table 1, 2 and 3.

Table 1. CNN-based encoder model parameter values

Module	Network layer	Model parameter
Coding module	Conv1d	N=16, K=11, S=4, P=5
	BatchNorm1d	N=16
	ReLU	-
	Conv1d	N=32, K=3, S=2, P=1
	BatchNorm1d	N=32
	ReLU	-
	Conv1d	N=32, K=3, S=1, P=1
	BatchNorm1d	N=32
	ReLU	-
	Conv1d	N=64, K=3, S=2, P=1
	BatchNorm1d	N=64
	ReLU	-
	Conv1d	N=64, K=3, S=1, P=1
	BatchNorm1d	N=64
	ReLU	-
	Conv1d	N=128, K=3, S=2, P=1
	BatchNorm1d	N=128
	ReLU	-
	Conv1d	N=128, K=3, S=1, P=1
	BatchNorm1d	N=128
	ReLU	-

3. Experiment

3.1. Dataset and Judgment Criteria

In this study, the full-life cycle dataset of bearings released by the PHM2012 [14] Data Challenge, which was collected by the PRONOSTIA experimental platform of the University of Franche-Comté, France, and is authoritative and widely comparable, is used for experimental validation. As shown in Figure 2, the experimental platform uses high-precision acceleration sensors (sensitivity of 100mV/g) to synchronize data acquisition in the horizontal and vertical directions, respectively, to ensure that multi-dimensional vibration characteristics are obtained. The dataset completely records the vibration data of 17 bearings under three typical operating conditions (different rotational speeds and load combinations) in the whole process from normal operation to complete failure, which provides a reliable benchmark for the remaining life prediction study, as shown in Table 4. In this paper, we adopt the “leave-one-out” method for the seven data of Case 1, when one of the bearing data is used as the test set, the other bearing data is set as the training set, and so on.

In order to comprehensively and objectively assess the prediction performance of the model, this study adopts two widely recognized regression evaluation indexes: mean absolute error (MAE) and root mean square error (RMSE). MAE intuitively reflects the size of prediction bias by calculating the average of the absolute errors between the predicted values and the true values; while RMSE amplifies the effects of larger errors by squaring operation, which is more sensitive to the prediction results’ The RMSE is more

Table 2. Parameter values of the decoder model based on transposed CNNs

Module	Network layer	Model parameter
Decoder module	ConvTranspose1d	N=128, K=3, S=2, P=5
	BatchNorm1d	N=128
	ReLU	-
	ConvTranspose1d	N=64, K=3, S=2, P=1
	BatchNorm1d	N=64
	ReLU	-
	ConvTranspose1d	N=64, K=3, S=2, P=1
	BatchNorm1d	N=64
	ReLU	-
	ConvTranspose1d	N=64, K=3, S=2, P=1
	BatchNorm1d	N=64
	ReLU	-
	ConvTranspose1d	N=64, K=3, S=2, P=1
	BatchNorm1d	N=64
	ReLU	-
	Conv1d	N=2, K=1, S=1, P=1

Table 3. Timing feature extraction module model parameter values

Module	Network layer	Model parameter
Timing Extraction Module	LSTM	N=512
	LSTM	N=128
	FC	N=64
	ReLU	-
	FC	N=32
	ReLU	-
	FC	N=16
	ReLU	-
	FC	N=1

sensitive to the degree of dispersion of the prediction results by amplifying the effect of larger errors through squaring operation. These two complementary indicators together constitute a complete system of model accuracy evaluation.

$$MAE = \frac{1}{n}\sum_{t=1}^{n}|er_i| \tag{13}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(er_i)^2} \tag{14}$$

where $er = RUL_{act} - RUL_{pred}$ is the error between the actual RUL and the predicted RUL, and n is the number of samples.

In the process of model training, considering the significant difference in the range of RUL values of each test bearing in the experimental data set, if the original RUL values are directly used for training, it may lead to the underfitting phenomenon of the model due to the large difference in the scale of the target variables, thus affecting the predic-

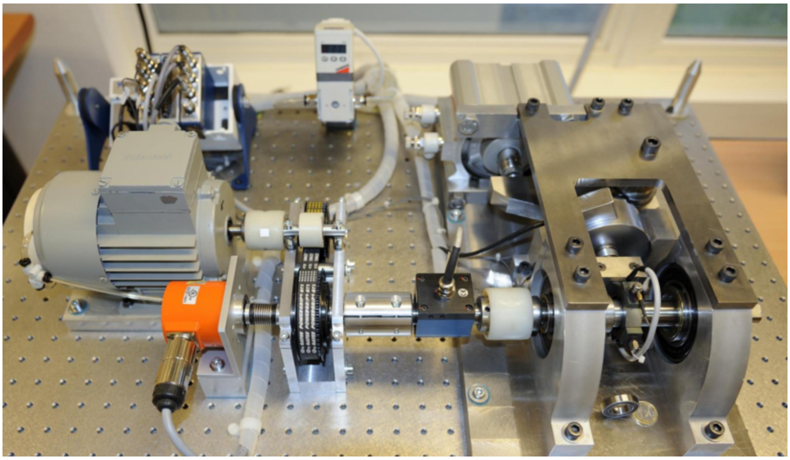

Figure 2. PRONOSTIA experimental platform.

tion performance. To address this problem, we adopt the linear normalization method to uniformly map the RUL values to the [0,1] interval, and the normalization calculation process is as follows:

$$RUL_{norm}^{t} = \frac{RUL^{t}}{RUL_{\max}} \tag{15}$$

where $RUL_{\max}$ denotes the longest RUL of the tested bearing, i.e., the RUL at the moment when the bearing starts running, RUL^{t} denotes the RUL of the bearing involved in the test at the moment t, and RUL_{norm}^{t} denotes the value of the RUL after normalization.

Table 4. Bearing operating conditions

Operating condition	Radial-force/kN	Rotation speed/rpm	Bearing serial number
condition1	4	1800	Bearing1_1 - Bearing1_7
condition2	4.2	1650	Bearing2_1 - Bearing2_7
condition3	5	1500	Bearing3_1 - Bearing3_3

3.2. *Implementation Rules*

During the experimental implementation of the model in this study, the experiments were conducted using the Adam optimizer [15] for model training, which combines the advantages of the momentum method and the adaptive learning rate, with the initial learning rate set to 10^{-4}, and the L2 regularization term weight factor of 10^{-3} was added to prevent overfitting. Considering the computational efficiency and memory limitation, the batch size was set to 32. The experimental hardware platform used NVIDIA RTX 4060 graphics card as RTX4060, and the GPU-specific memory size was 8 G. In the data pre-processing stage, we implemented the maximum-minimum normalization on the input data, linearly transforming all features to a uniform scale to eliminate the effect of the difference of the magnitude on the training of the model. In order to enhance the model generalization ability, a random sampling strategy was adopted as a data enhancement means in the training phase, and the sampling length was kept consistent with the original data. In the model testing phase, we use the original unenhanced data as input, and the whole training process lasts for 50 epochs. The hyperparameters α and α in the joint loss function, we set them to 2 and 1.

3.3. Experimental results

In this paper, the performance of the proposed model SFENet is compared with other models on PHM2012 dataset as shown in Table 5. From Table 5, it can be seen that SFENet has lower MAE and RMSE compared to the other two models.

First, it can be observed from Table 5 that for the Bearing1_1 bearing model, SFENet has a MAE of 0.072 and a RMSE of 0.084, both of which show that SFENet has a lower prediction error compared to DCCET[16] and TCN+MA[17], suggesting a higher prediction accuracy. Then, for the Bearing1_2 bearing model, the MAE of SFENet is 0.093 and the RMSE is 0.113, which are also better than the other models, further verifying the superior performance of SFENet on this bearing model. However, on the Bearing1_6 bearing model, although the MAE and RMSE of all models are generally high, the MAE of SFENet is 0.093 and the RMSE is 0.123, which are still the lowest among all models, showing that it still maintains a better prediction performance in complex situations.

Overall, the SFENet method performs well in predicting the remaining bearing life on the PHM2012 dataset. Compared with models such as DCCET[16] and TCN+MA[17], SFENet demonstrated lower prediction errors and higher prediction accuracy on multiple bearing models. This demonstrates that SFENet is able to effectively process and analyze complex vibration signal data to more accurately predict the remaining service life of bearings.

Table 5. Performance comparison of SFENet with other models on PHM2012 dataset

Bearing type	DCCET[16]]		TCN+MA[17]]		SFENet	
	MAE	RMSE	MAE	RMSE	MAE	RMSE
Bearing1_1	0.048	0.068	0.085	0.096	0.072	0.084
Bearing1_2	0.130	0.150	0.114	0.132	0.093	0.113
Bearing1_3	0.101	0.126	0.102	0.115	0.035	0.045
Bearing1_4	0.079	0.094	0.212	0.264	0.130	0.162
Bearing1_5	0.123	0.174	0.196	0.267	0.075	0.106
Bearing1_6	0.148	0.174	0.153	0.186	0.093	0.123
Bearing1_7	0.141	0.173	0.170	0.255	0.062	0.080

We show the comparative results of the RUL prediction performance of the four bearings Bearing1_1, Bearing1_2, Bearing1_3 and Bearing1_7 in Figure 3. The figure employs a blue diagonal line to mark the actual RUL trend, a red curve to indicate the prediction results of the SFENet model, and a light blue bar graph to visualize the predic-

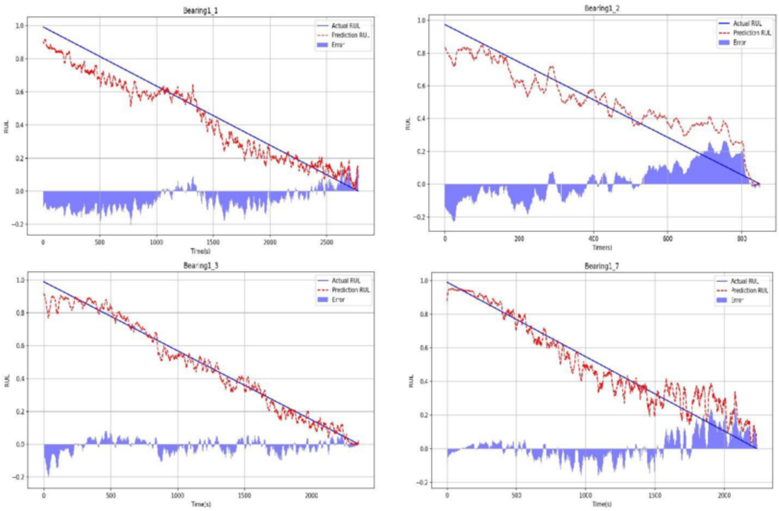

Figure 3. RUL prediction performance on Bearing1_1, Bearing1_2, Bearing1_3 and Bearing1_7.

tion error. It is particularly noteworthy that in the prediction case of Bearing1_3, SFENet shows excellent prediction accuracy, and its red prediction curve and blue actual curve show a high degree of agreement, which indicates that the model is able to accurately capture the degradation pattern of the bearing. In contrast, the prediction results of other bearings have slight deviations, but the overall trend is still in good agreement with the actual RUL, and the visualization results fully prove that SFENet has excellent performance in the field of bearing life prediction.

3.4. Ablation experiment

In this section, we conduct ablation experiments in PHM2012 dataset Case 1 with Bearing1_3 as the test set and other data as the training set to further validate the effectiveness of each component of the model, using MAE and RMSE as the metrics.

Table 6. Ablation studies of decoders

Bearing type	Original Decoder			
	No		Yes	
	MAE	RMSE	MAE	RMSE
Bearing1_3	0.058	0.073	0.035	0.045

Decoder ablation. In exploring the role of decoder in the prediction of RUL of bearings, we compared the performance with and without decoder as shown in Table 6. As can be seen from the table, for the bearing model Bearing1_3, when the decoder is not used, the MAE is 0.058 and the RMSE is 0.073.This indicates that the model has been able to predict the bearing RUL with some degree of accuracy without the aid of the decoder. However, when the decoder is introduced, the MAE decreases significantly to 0.035 and the RMSE also decreases to 0.045.This change suggests that the addition of the decoder greatly improves the prediction accuracy of the model. By extracting richer features or optimizing the data representation, the decoder enables the model to learn and understand the failure modes of the bearings more effectively.

Ablation of the BN layer. In exploring the role of the BN layer in the codec, we performed a detailed analysis based on the data provided, as shown in Table 7. From the table, it can be observed that for the bearing model Bearing1_3, without the BN layer, the MAE is 0.061 and the RMSE is 0.081. This indicates that in the absence of the BN layer, the predictive performance of the model, although present, is not optimal. However, when the BN layer is introduced, the MAE is significantly reduced to 0.035 and the RMSE is reduced to 0.045.This significant change suggests that the addition of the BN layer positively affects the model performance.The BN layer helps to speed up the training process of the model by normalizing each batch of input data, improving its generalization ability and potentially preventing the problem of vanishing or exploding gradients, which makes the model able to learn the distribution and characteristics of the data more accurately.

Table 7. Ablation studies of BN layer

Bearing type	BN layer			
	No		Yes	
	MAE	RMSE	MAE	RMSE
Bearing1_3	0.061	0.081	0.035	0.045

The ablation of encoder layers. We conducted ablation experiments on the convolutional layers in the encoder, and the experimental results are shown in Table 8. The number of layers in the encoder has a significant impact on the model performance. Among them, the 7-layer encoder performed the best on the Bearing1_3 dataset, with MAE and RMSE reaching 0.035 and 0.045, reducing errors by 27.1% and 23.7% compared to the 6-layer encoder. However, when the number of layers increased to 8, there was a significant degradation in model performance, with MAE and RMSE both recovering to levels close to the 6-layer model, with MAE and RMSE being 0.046 and 0.059, respectively. This indicates that a too deep network structure may lead to optimization difficulties or overfitting issues, and a 7-layer encoder achieved the best balance between model complexity and performance.

Table 8. Ablation research on the encoder layers

The number of layers in the encoder	6		7		8	
	MAE	RMSE	MAE	RMSE	MAE	RMSE
Bearing1_3	0.048	0.059	0.035	0.045	0.046	0.059

Ablation of Sequence Feature Extraction Modules. In the ablation study of sequence feature extraction module, we compared the performance of GRU, LSTM and their bi-directional variants Bi-GRU and Bi-LSTM in the prediction of RUL of bearings as shown in Table 9. From the table, it can be observed that for the bearing model Bearing1_3, when GRU is used as the sequence feature extraction module, the MAE is 0.079 and the RMSE is 0.094. This indicates that GRU is able to capture the fault features in the sequence data to a certain extent, but the performance is not optimal. When LSTM is used instead of GRU, the MAE is reduced to 0.035 and the RMSE is also reduced to 0.045.This significant enhancement indicates that LSTM is more capable of processing the sequence data and is able to extract the features associated with the bearing faults more efficiently. Further, when a bi-directional structure, i.e., Bi-LSTM, is introduced, the MAE is further reduced to 0.034, and the RMSE is also slightly reduced to 0.044. This suggests that the bi-directional structure is able to capture the contextual information in the sequential data in a more comprehensive manner, thus enhancing the prediction accuracy of the model. However, the MAE and RMSE performance is only improved by 0.001, yet more number of parameters and computational effort are introduced. In contrast, although Bi-GRU also adopts a bi-directional structure, its MAE of 0.050 and RMSE of 0.067 are higher than that of Bi-LSTM.This may be due to the fact that LSTM has a better performance in dealing with long sequential data, whereas GRU, although it performs well in some cases, is a little inferior in this experiment.

In summary, the selection of sequence feature extraction modules has a significant impact on the performance of bearing fault diagnosis. In this experiment, LSTM achieved the best balance between performance and efficiency.

Table 9. Ablation studies of Sequence Feature Extraction Modules

Bearing type	GRU		LSTM		Bi-LSTM		Bi-GRU	
	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE
Bearing1_3	0.079	0.094	0.035	0.045	0.034	0.044	0.050	0.067

4. Conclusion

In this paper, a novel end-to-end codec feature enhancement based prediction method is innovatively proposed, which has a unique processing flow and significant advantages. First, feature extraction and enhancement operations are performed on the original data with the help of self-codecs to fully explore the potential information in the data. Next, the enhanced features are fed into a multilayer LSTM to realize the effective extraction of temporal features. Subsequently, RUL prediction is further carried out through multiple fully connected layers. Finally, multiple MSE loss functions are applied to complete the training of the model to ensure the accuracy and stability of the model. The experimental results fully demonstrate the effectiveness of the model proposed in this paper, which exhibits competitive performance and provides a new and reliable solution for bearing RUL prediction.

Due to the complex and ever-changing working environment of bearings, there are significant differences in data distribution under different equipment and operating conditions (such as load, speed, temperature differences). The remaining life prediction model of bearings proposed in this paper needs to be fine-tuned in different types of bearings under different operating conditions. Furthermore, in order to address the issues of model lightweighting and small sample size, we will conduct further research in the future to enhance the application value of the model in practical industrial scenarios.

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Research on the Governance Mechanism of Short Video Media Ecology Empowered by "5G+AI" Dual Engine

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Abstract: The high bandwidth and low latency characteristics of 5G networks, combined with continuous advancements in Artificial Intelligence (AI) technology, have not only expanded their application scenarios but also ushered in a new era of media characterized by faster, smarter, and more personalized development. This paper reviews the current research status of 5G and AI technologies in the short video sector, focusing on Xi Jinping's "Internet View" and systematically organizes the relevant theories of short video media ecological governance. It constructs a "5G+AI" dual-engine model to empower the short video media ecosystem and analyzes the inter- action between 5G and AI technologies, which together enhance the governance of the short video media ecology and facilitate the healthy development of the short video industry. This approach aims to provide users with a clear, healthy, and beneficial online environment. Research on the governance mechanisms of the short video media ecology is essential for promoting and practicing core socialist values, asserting initiative and leadership in cyberspace, and serves as a crucial measure to advance and improve the level of internet governance.

Keywords: 5G, AI, Short video media, Ecological governance

1. Introduction

Against the backdrop of accelerated global digital transformation, the fifth-generation mobile communication technology (5G) has built a network infrastructure for the interconnection of people, machines, and things, with high-speed, low latency, and large connectivity as its core features. In recent years, countries have accelerated the construction of 5G networks, and the popularity of 5G terminal devices (such as smartphones) has significantly increased, laying a hardware foundation for the development of the digital economy. At the same time, artificial intelligence (AI)

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technology has made breakthrough progress in fields such as deep learning, computer vision, and natural language processing. Its cross-industry applications have deeply reshaped production and lifestyle, becoming the core technology engine driving social change.

The impact of "5G+AI" technology on short video media presents a dual feature of technological empowerment and ecological reconstruction: at the level of technological empowerment, the high-speed characteristics of 5G eliminate the buffering delay of video transmission, allowing users to enjoy an instant viewing experience of "click and see", and enhancing user stickiness from the bottom level of technology; Its high bandwidth support capability drives short video platforms to break through resolution limitations, achieve the popularization of 4K/8K ultra high definition content, and build immersive visual experiences. The low latency characteristics of 5G have further revolutionized live streaming interaction scenarios, and real-time interactions between users and hosts (such as bullet comments and live streaming) have broken free from the constraints of traditional network latency, significantly enhancing the sense of participation and presence. At the level of ecological reconstruction, AI technology assists short video creation through content generation models (such as AIGC), reducing the threshold for professional content production (PGC). At the same time, an intelligent review system based on natural language processing and image recognition efficiently filters out harmful content such as violence and pornography, improving the efficiency of platform content governance; AI algorithms construct personalized recommendation models by mining user behavior data, achieving content distribution with "thousands of people, thousands of faces", and reshaping the paradigm of information dissemination while improving user retention.

However, the wild growth of the short video industry and the disorderly release of technological dividends have triggered a deep-seated crisis in the media ecosystem. The anonymity and openness of the Internet, together with the "addictive algorithm" driven by capital, have led to platform content, which is vulgar and homogeneous. The "information cocoon room" has restricted users' cognitive expansion, and privacy leakage and copyright infringement incidents have occurred frequently. In extreme cases, there is even the risk of ideological penetration and value distortion. These issues not only expose the ethical deficiencies in the application of technology but also highlight the practical contradiction of the industry governance system lagging behind technological development.

Although existing literature has extensively discussed topics such as the improvement of short video transmission efficiency by 5G technology and the application of AI algorithms in content recommendation, there are still three research gaps:

(1) Insufficient systematic research on the synergistic effects of technology: Current research mostly analyzes the impact of 5G or AI single technology on the short video industry in isolation, lacking a systematic exploration of how the integration of "5G+AI" technology can reconstruct the industrial ecosystem. For example, the collaborative mechanism between the low latency characteristics of 5G and the real-time data processing capabilities of AI in live streaming e-commerce scenarios, as well as the deep impact of this mechanism on user consumption behavior, has not yet formed a complete theoretical framework.

(2) Long term observation of social and cultural impacts is lacking: Existing research focuses on the short-term effects of technology applications (such as user activity and platform traffic), but lacks empirical research based on longitudinal data on

how the "5G+AI" driven content production and consumption patterns shape public cognition, reconstruct media literacy, and affect intergenerational communication and other long-term social and cultural effects. Especially the potential harm of "information cocoons" and "algorithmic discrimination" to the formation of values among young people urgently requires in-depth analysis from an interdisciplinary perspective.

(3) Theoretical lag in governance system innovation: Faced with emerging issues such as algorithm abuse and privacy security, existing research mostly stays at the level of phenomenon description or policy interpretation and has not yet constructed a governance theoretical framework that combines technological adaptability and cultural applicability. For example, how to balance the vitality of technological innovation with social public interests, and how to design a collaborative governance mechanism that accommodates multiple stakeholders (government, platform, users), still needs to break through the limitations of traditional regulatory paradigms from a theoretical perspective.

In summary, our major contributions are summarized as follows:

- Research on innovative media theory enriches media ecology. By integrating 5G and AI technologies, it can expand and deepen traditional media theory research, providing new theoretical perspectives and methodologies for the governance of short video media ecology. This research combines multiple disciplines, including information science, communication studies, and sociology, promoting the application of interdisciplinary theories and methods in the field of media governance. It contributes to enriching media ecology theory, particularly in exploring how technological advancements affect media ecological balance and governance mechanisms.
- From a practical perspective, optimizing the content ecosystem, enhancing governance efficiency and public literacy, and guiding the correct social values are essential. The integration of 5G and AI technologies can provide more efficient solutions for the governance of short video media ecosystems, improving the efficiency of content review, distribution, and regulation. Building a healthier and more orderly short video content ecosystem will promote the creation and dissemination of high-quality content while curbing the spread of harmful information. Through research on media ecosystem governance mechanisms, we can enhance the public's understanding of the impact of 5G and AI technologies on short video media ecosystems, as well as improve public internet literacy and self-protection awareness. At the same time, a good media ecosystem governance mechanism helps to disseminate the core socialist values, guide the healthy development of online culture, and create a positive and uplifting online environment.

The remainder of this paper is structured as follows. In Section II, we demonstrate existing approaches. In Section III, we introduce theoretic Framework. We present a short video ecosystem model empowered by "5G+AI" dual engine in Section IV. In Section V, how to build an ecological governance mechanism. Finally, we conclude the paper in section VI.

2. Related Work

According to the "Current Status and Development Report of Short Video Research in China," research in the short video field can be divided into three stages: the budding period (2007-2011), the development period (2012-2015), and the soaring period (2017-2023).

In recent years, the volume of published research on short videos has continued to rise, especially in 2020, approaching 900 papers per year. This indicates that short video research is gradually becoming a hot topic in academia. [1] Li Liangrong and Xin Yanyan's article "From 2G to 5G: The Transformation of China's Media Industry Driven by Technology" explores how technology has driven the transformation of China's media industry from the 2G to the 5G era, particularly in terms of ideological concepts, platform development, and media convergence. [2] Zhang Mingxin and Chang Mingzhi's article "The Prospects of Media Convergence Development in the Context of 5G Applications" analyzes the impact of 5G technology on media, content, and user understanding, as well as the changes in the relationship between media and related industries. [3] Wu Tao and Zhang Zhian's article "Media Transformation and Opportunities for Mainstream Media Under the Influence of 5G" discusses how 5G technology profoundly affects media transformation and brings new development opportunities for mainstream media. [4] Li Yuan's article "Trends and Application Research of Digital Media Art Development Based on 5G Technology" conducts an in-depth study of the application trends of 5G technology in the field of digital media art. [5]The "5G Converged Media Application Research Report (2020)" was jointly compiled by China Telecom, the New Media Research Institute of Communication University of China, and Guangming Online. It focuses on presenting the application, impact, expansion, and innovation of 5G technology in promoting the development of media convergence. These documents cover various aspects of 5G technology in the media field, including technological development, changes in the media industry, media convergence, and the application of digital media arts, providing rich information and perspectives for researching the application of 5G technology in the media field.

[6] "Progress and Applications of Recommendation System Research" reviews the development of recommendation systems over the past five years, including aspects such as datasets, algorithms, and performance evaluation, and discusses the system architecture of recommendation systems in internet application scenarios. [7] "A Survey of Intelligent Recommendation Systems" by Hu Qi et al. analyzes the advantages and disadvantages of traditional recommendation algorithms, summarizes the research progress of deep learning technologies in recommendation systems, and looks forward to the future development direction of intelligent recommendation systems. [8] "Content Recommendation and Review: The Secrets Behind the Algorithms" delves into the operational principles of content recommendation systems and how advanced algorithms are used for content review and information filtering to achieve efficient content recommendation and strict security control. [9] "The Era of Intelligent Review: How Artificial Intelligence is Changing Content Filtering" introduces the definition and principles of intelligent review and its applications in different types of content review, such as text review, image review, and video review, while exploring how AI technology is changing the current and future landscape of content filtering. [10] "Design and Application of an AI-Based Text Content Review System" presents the design and application of an AI-based text content review system, emphasizing its importance in educational video resource service systems. [11] "AI

Content Review: The Future of Intelligent Review" discusses the definition and principles of AI review and its applications in various scenarios, such as text review, image review, and video review, while looking ahead to the future development of AI content review.

The rapid development of short videos has also brought regulatory challenges. Issues such as varying content quality, copyright infringement, and counterfeit sales have become increasingly prominent. For example, some short video platforms recommend vulgar and superficial content to attract users, even involving violent and pornographic information. Additionally, with the rise of fan economy and e-commerce platforms, the short video industry has seen behaviors such as copyright infringement and the sale of counterfeit goods, which continuously challenge legal boundaries and the strength of industry regulation. Furthermore, there is the issue of staged short videos within the creative ecosystem. These videos are artificially planned, fabricated, and performed, but are disguised as real news events for dissemination, affecting users' perception of the real world, damaging the online ecosystem, and even exacerbating social conflicts. To address this issue, it is necessary to establish a long-term governance mechanism for short video platforms, differentiate the marketing and political motives behind staged content for classification and handling, create a comprehensive information evaluation system, and pay attention to the values embedded in algorithms. With the development of 5G technology, the content ecosystem of short videos faces opportunities and challenges for transformation and upgrading. 5G technology will promote the diversified development of short video content forms, such as the application of virtual reality and AI technology, while also bringing challenges to the reconstruction of the content ecosystem. How to regulate and guide the development of the short video content ecosystem has become an important topic.

3. Theoretic Framework

3.1 The characteristics of 5G and AI

5G technology is the abbreviation for the fifth generation of mobile communication technology. It adopts a completely new technological architecture and spectrum utilization method, featuring higher data transmission rates, lower latency, greater network capacity, and better connection stability.

AI is a technology that simulates human intelligence. Unlike traditional computer programs, it can mimic human thinking to complete tasks that require intelligence, such as autonomous driving, speech recognition, image recognition, natural language processing, etc. Artificial intelligence is a comprehensive science that involves theoretical foundations from multiple fields in its development, such as mathematics, philosophy, psychology, neurology, computer science, etc. The theoretical foundation of AI covers data collection and processing, model construction and training, inference and decision-making, algorithms and data processing, knowledge representation and reasoning, perception and cognition, machine learning and deep learning, supporting the development and application of AI technology. The development and application of 5G and AI technologies are mutually reinforcing. 5G provides a network environment with high bandwidth, low latency, and high connection density, providing infrastructure support for AI's real-time data processing and intelligent decision-making. Meanwhile, AI technology can also optimize 5G networks, improve their efficiency and service quality. Both have jointly promoted the development of many emerging applications, such as intelligent manufacturing, smart cities, and telemedicine.

3.2 Theoretical Framework for Ecological Governance of Short Video Media

[12-15] In the new historical context and governance reform, Xi Jinping's "Internet view" has overall made new plans and explorations for the ecological governance of short video media, proposing new principles and new requirements. This provides scientific guidance and action guidelines for achieving a three-dimensional "integrated" governance and a directive "empowerment" governance. This article attempts to construct a strategy for the ecological governance mechanism of short video media, which includes injecting mainstream values into technological algorithms and enhancing platform social responsibility; improving media literacy and focusing on regular educational management in terms of conscious awareness; and ensuring effective top-level design and building a collaborative governance pattern in terms of order regulation.

The theoretical framework for the governance of short video media ecology is shown in Figure 1. The theoretical foundation mainly includes media ecology theory, governance theory, and information technology theory. The core elements of the theoretical framework are: governance subjects (including government, enterprises, society, and the public), governance objects (including content quality, user behavior, and platform responsibility), governance mechanisms (including technical mechanisms, legal mechanisms, market mechanisms, and educational mechanisms), and governance goals (including maintaining information security, ensuring content health, promoting fair competition, and enhancing user experience). It operates according to the process of "monitoring and identification" → "evaluation and decision-making" → "execution and feedback" → "continuous optimization".

The theory of media ecology includes core concepts of media ecology, such as media environment, media niche, and media interaction. Governance theory: an overview of the basic principles of governance theory, including multi-stakeholder participation, rule of law principles, transparency, and accountability. Information technology theory: exploring the role of information technologies such as 5G and AI in the media ecology of short videos.

(1) Utilize "5G+AI" to achieve intelligent review, regulation, and recommendation of short videos and other self-media platforms.

5G+AI technology in the field of self-media short videos has advantages such as high-speed, low-latency transmission performance; powerful data analysis and processing capabilities; and real-time, comprehensive, and precise short video content management. This strengthens the construction of intelligent review, supervision, and recommendation systems for self-media. It helps improve content quality, ensures a clear online space, and meets users' personalized needs.

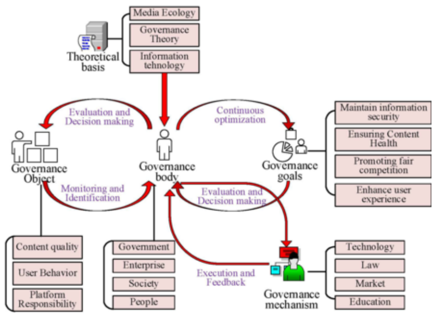

Figure 1: Theoretic Framework.

(2) “Four-in-One” Short Video Media Ecological Governance Mechanism

The “four-in-one” short video media governance mechanism involves the collaborative effort- s of government regulation, platform self-discipline, social supervision, and user participation to jointly build a good order for the online public opinion ecology in the era of self-media. In terms of technological algorithms, mainstream values should be injected to enhance the social responsibility of platforms; in content production, there should be a focus on vertical fields to create a positive energy ecosystem; in terms of awareness, public media literacy should be improved with an emphasis on regular educational management; and in terms of order regulation, top-level design should be well executed to create a collaborative governance pattern.

(3) The operational process of the theoretical framework

Step 1: monitoring and identification. Use technological means to monitor the short video media ecosystem and identify potential risks.

Step 2: assessment and Decision-Making. Evaluate risk levels and develop governance strategies.

Step 3: execution and feedback. Implement governance measures, collect feedback information, and adjust governance strategies.

Step 4: continuous optimization. Continuously optimize the governance framework based on governance effectiveness and changes in the external environment.

4. A Short Video Ecosystem Model Empowered by “5G+AI” Dual Engine

To build a theoretical framework for the governance of the short video media ecosystem empowered by the dual engines of “5G + AI,” it is necessary to consider how 5G and AI technologies jointly influence the production, distribution, consumption, and regulation of short video content, as well as how these technologies drive the overall transformation of the media ecosystem. At the same time, attention must also be paid to the new challenges and issues brought about by technological changes, such as content quality, information security, and user privacy protection. The theoretical framework for short video media empowered by the dual engines of “5G + AI” is shown in Figure 2.

[16] The main participants in the short video platform ecosystem include platform operators, con- tent producers, and content consumers. Platform operators are responsible for the construction and operation of the platform, continuously improving recommendation algorithms and optimizing recommendation rules by collecting and

analyzing user data, as well as providing specialized services to attract more content producers and consumers to join the platform. Stakeholders in the short video platform ecosystem also include Multi-Channel Network (MCN) service provider- s, advertisers, and regulatory bodies, which support the platform's operation from commercial, policy, and service perspectives. Content producers use platform technology and necessary equipment to shoot and edit short videos, providing high-quality short video content for the platform. Content consumers spend time and data costs browsing short videos to gain spiritual satisfaction, providing the traffic value that is most needed for the platform's development. There is a network effect between content consumers and content producers, where their interactions jointly promote the platform's operation. There exists a non-monetary transaction relationship between content producers and content consumers, where producers invest time and effort to create quality content in hopes of gaining the attention and interaction of consumers. The larger the scale of content producers and consumers, the greater the value they can potentially gain through direct and indirect network effects.

In addition, the new generation of information technology "5G+AI" empowered by the short video media ecosystem model generates indirect network value among platform operators, content producers, and content consumers, while empowering the integration of media ecology, content ecology, news production, and enhancing user experience. The specific functions are as follows:

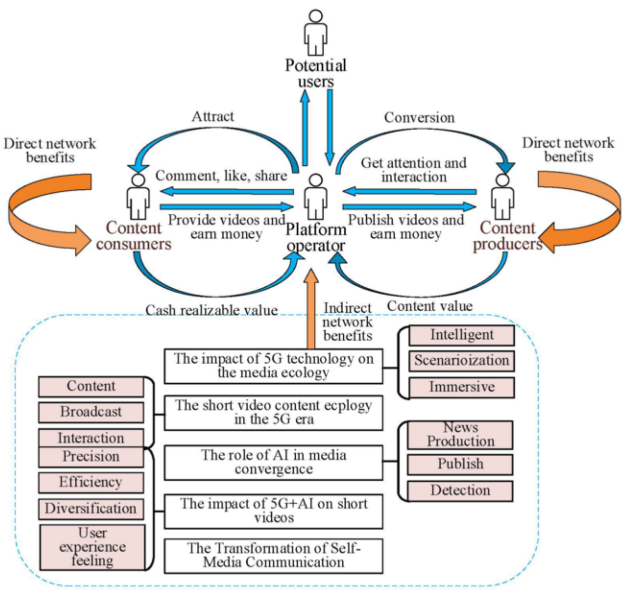

Figure 2: Ecological Modelling.

The impact of 5G technology on the media ecosystem: 5G technology not only promotes changes in the media ecosystem and the dissemination pattern but also becomes an important node in the evolution of dissemination. 5G technology will reshape the relationship between people, media, and society, promoting the development of the communication field towards a new direction of intelligent, visual, scene based, and immersible communication.

The changes in the short video content ecosystem: 5G technology brings opportunities for leapfrog development to the short video content ecosystem, including multiple aspects such as content production, dissemination, and interaction. This opportunity is reflected in the innovation of short video content forms and the expansion of content functions, providing the basic technical conditions for the implementation and landing of short videos. However, the transformation of the short video content ecosystem also faces some bottlenecks, such as changes in operational logic and technological challenges.

The role of AI in media convergence: For example, the "Media Brain" platform jointly built by Xinhua News Agency and Alibaba integrates big data and artificial intelligence technologies to provide media organizations with the ability to produce, distribute, and monitor news. This integrated application represents the deep integration of artificial intelligence technology in the media field. The impact of the combination of 5G and AI on short videos: The combination of 5G technology and artificial intelligence has brought about an improvement in user experience and a revolution in production methods for short videos. For example, the high transmission speed and low latency characteristics of 5G, combined with AI technology, can promote the diversified development of short video content forms, such as virtual reality, high-definition video production, etc.

The transformation of self-media communication: self-media communication empowered by 5G technology, such as China Mobile Migu's innovative attempt in the field of 5G short video, demonstrates how 5G can promote the transformation of media forms, including new media forms such as integrated media mobile newspapers and ultra-high definition video ringback tones.

5. How to Build an Ecological Governance Mechanism Through Case Analysis

[17] The specific content of the short media ecological governance mechanism is shown in Figure 3. Mainly from five aspects: policies and regulations, technical means, platform responsibilities, multi-party collaboration, and flexible control.

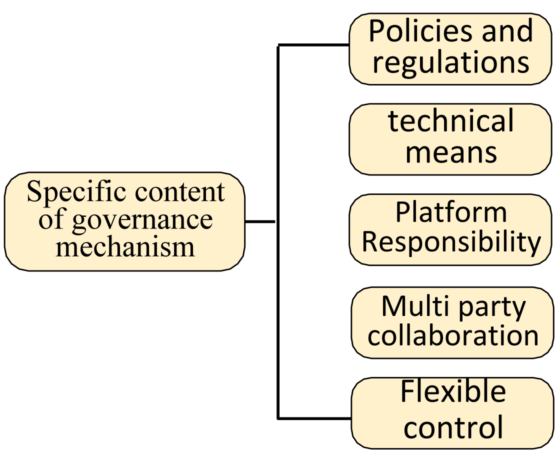

Figure 3: Specific content of governance mechanism.

(1) Policies and regulations. Policies and regulations are the foundation for the ecological governance of short video media, ensuring that governance work has legal basis [18]. The specific content includes:

Personal Information Protection: In accordance with the Personal Information Protection Law, we protect user privacy and data security to prevent the misuse of user information.

Content audit policy: formulate and implement the Management Regulations on Internet Information Service Algorithm Recommendation, standardize the content audit mechanism of short video platform, and ensure the health and legitimacy of content.

Cybersecurity Law: In accordance with the Cybersecurity Law, strengthen the supervision of short video platforms, ensure that platforms operate in accordance with the law, and implement their main responsibilities.

(2) Technical means. Technical means are the core of the ecological governance of short video media, mainly including the following aspects:

Intelligent Content Review: Utilizing AI technology to automatically review short video content, quickly identifying and filtering illegal and harmful information through image recognition, speech recognition, and natural language processing technologies.

User behavior analysis: By analyzing user behavior data through AI technology, abnormal behaviors such as brushing volume, false comments, etc. can be identified for targeted governance.

Public opinion monitoring and guidance: AI technology can monitor online public opinion in real-time, detect and process negative information in a timely manner, and recommend positive and healthy short video content through algorithm optimization.

(3) Platform responsibility. Short video platforms bear important responsibilities in ecological governance [19], including:

Content review mechanism: The platform should establish a sound content review mechanism to ensure that all uploaded short video content complies with laws, regulations, and socialist core values.

User management: The platform should strengthen user management, establish a user credit system, and restrict and handle non-compliant users.

Technical support: The platform should continuously improve its technological level and utilize AI and big data technologies to enhance its content review and public opinion monitoring capabilities.

(4) Multi-party collaborative governance. The governance of the short video ecosystem requires the joint participation of multiple parties such as the government, platforms, and users, including **Government regulation:** The government should strengthen supervision of short video plat- forms to ensure that they operate in accordance with the law and fulfill their main responsibilities. **Platform self-discipline:** Short video platforms should strengthen self-discipline, improve internal management mechanisms, strictly abide by laws and regulations, and establish fair and transparent governance rules.

User participation: Encourage users to actively participate in the governance of the short video ecosystem and jointly maintain a good online environment through reporting mechanisms and community supervision.

(5) Flexible shutdown mechanism. Establish a flexible shutdown mechanism for user generated content (UGC), including:

UGC role cognition: By setting exam “checkpoints”, enhance UGC’s role cognition awareness and sense of responsibility, and encourage them to consciously abide by platform rules and social norms.

Grading management system: Establish a UGC grading system, manage users based on their reputation and content quality, incentive high-quality content creators, and restrict non-compliant users.

User reporting mechanism: Encourage users to report illegal and harmful information, establish a sound reporting and handling mechanism, and create a positive interactive community environment.

Through the above measures, a short video media ecosystem governance mechanism based on policies and regulations, technological means, platform responsibilities, and multi-party collaborative governance can be constructed, effectively improving the quality and security of the short video ecosystem. Implementation plan and steps of governance mechanism.

6. Conclusion

We discussed the application of "5G+AI" technology integration in the short video industry and its impact on media ecological governance mechanisms. The integration of "5G+AI" technology not only offers a novel practical pathway for the ecological governance of short - video media but also significantly improves content review efficiency and reduces governance costs. Additionally, it enables personalized recommendations for short - video content, enhances the user experience, and effectively curbs the dissemination of harmful information. To this end, the government and enterprises should increase their investment in "5G+AI" technology to facilitate its broader application in the governance of the short - video media ecosystem. Future research could further explore the legal implications of "5G+AI" technology applications in the short video industry and the influence of emerging development trends.

[20-22] However, this study has several limitations. First, the examination of the social impact of "5G+AI" technology remains incomplete. Specifically, more in-depth research is needed on potential public cognitive biases and the technology's influence on the value systems of young people. Second, existing studies predominantly focus on the direct relationship between technology and governance, overlooking the significant role that cultural disparities and diverse policy environments across regions play in determining the effectiveness of "5G+AI" technology implementation. This oversight limits the universality of governance strategies. Third, there is a dearth of research on the potential risks and challenges posed by emerging functions within the context of technological applications for governance, such as AI generated virtual hosts and 5G enabled real-time interactive live streaming.

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Application of Knowledge Graphs in Intelligent Search Engines

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Abstract. As a core technology of structured semantic networks, knowledge graphs significantly enhance the semantic understanding and reasoning capabilities of intelligent search engines. This paper systematically analyzes the applications of knowledge graphs in scenarios such as entity search, complex question answering, and related recommendations. It explores their technical implementation paths and validates their effectiveness through typical cases (Google Knowledge Graph, Baidu Zhixin). The aim of this paper is to study how knowledge graphs empower intelligent search engines, analyze their technical challenges and development directions, and look ahead to the future trends of the integration of knowledge graphs with large models and multi-modal technologies.

Keywords. Knowledge Graph; Intelligent Search Engine; Semantic Network; Multi-hop Reasoning

1. Introduction

A knowledge graph is a structured and semantic knowledge representation model that stores knowledge in a graph - like structure [1]. The concept of the knowledge graph originated from artificial intelligence and was first proposed by John McCarthy, a computer scientist at Google. In the 1960s, the semantic network, as a method of knowledge representation, was first proposed by Quillian, laying the theoretical foundation for the knowledge graph. It was not until 2012 that Google officially introduced the concept of Knowledge Graph and began to use it in its search engine, marking an important development stage for knowledge graphs [2].

2. Related Research

2.1 Knowledge Graph

A knowledge graph is a structured and semantic knowledge representation model that stores knowledge in a graph-like structure. The concept of the knowledge graph

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originated from artificial intelligence and was first proposed by John McCarthy, a computer scientist at Google. In the 1960s, the semantic network, as a method of knowledge representation, was first proposed by Quillian, laying the theoretical foundation for the knowledge graph. It was not until 2012 that Google officially introduced the concept of Knowledge Graph and began to use it in its search engine, marking an important development stage for knowledge graphs.

Knowledge graphs have gradually formed a complete system, mainly encompassing tasks such as entity recognition, relation extraction, knowledge representation, and knowledge fusion. Named entity recognition serves as the research foundation and a crucial task for knowledge graphs. It is equivalent to a sequence labeling problem. By identifying entity boundaries from natural language, machine learning algorithms are employed to classify and label entities [3]. Knowledge graphs possess the following core characteristics:

(1) Structured representation: Different from the tabular form of traditional databases, knowledge graphs store data in a "graph" format, which aligns better with human cognition.(2) Semantic association: They emphasize the logical relationships between entities rather than simple keyword matching.(3) Inferability: They support multi-hop reasoning.(4) Multi-source fusion: They integrate multi-modal data from various sources such as texts, databases, and sensors to form a unified knowledge base.

2.2 Technical Architecture of Knowledge Graphs

The technical architecture of knowledge graphs mainly consists of five core modules: knowledge acquisition, knowledge representation, knowledge storage, knowledge reasoning, and knowledge application [4]. The overall architecture design aims to extract structured knowledge from multi-source heterogeneous data and support applications such as intelligent search and question-answering systems through semantic associations.

Knowledge acquisition is the basis for constructing knowledge graphs. Its main task is to extract entities, attributes, and relationships from unstructured or semi-structured data to form structured triples (subject, relation, object). Specific technologies include data sources and information extraction techniques. Knowledge representation aims to convert the extracted triples into a form that can be processed by computers, which is divided into symbolic representation and vector representation. The storage of knowledge graphs needs to support efficient querying and expansion. The main solutions include graph databases, triple stores, and hybrid storage [5]. The knowledge reasoning module is used to complete missing knowledge or discover implicit relationships. The main methods include rule - based reasoning, embedding - based reasoning, and temporal reasoning. Knowledge application: The ultimate goal of knowledge graphs is to provide support for upper - layer applications. Typical scenarios include intelligent search engines, question - answering systems, recommendation systems, and risk analysis.

2.3 Knowledge Graph - based Intelligent Question - Answering Technology

The implementation of knowledge graph - based intelligent question - answering needs to solve three aspects of problems: question understanding, knowledge acquisition, and answer generation [6]. The first step, question understanding, refers to using certain techniques to transform natural language questions raised by people into a structured form that computers can understand and process. Question understanding includes word segmentation, semantic annotation, keyword extraction, entity recognition, syntactic analysis, and intention recognition. The second step, knowledge acquisition, is the core link in realizing question - answering technology, which refers to the process of obtaining corresponding knowledge by constructing a queryable knowledge base. The third step, answer generation, is to present the generated answers to users, which is a key link in direct interaction with users. Usually, it can be achieved through two methods: template generation or natural language generation (NLG). There are three common methods for implementing knowledge graph question- answering systems: semantic parsing - based methods, retrieval - ranking - based methods, and deep - learning - based methods.

3. Research Methods

3.1 Literature Research Method

Collect literature materials regarding knowledge graphs, intelligent search engines, and the combined applications of the two channels such as academic databases, industry reports, and professional books. For example, searching for relevant academic papers in databases like IEEE Xplore and ACM Digital Library to understand the existing research achievements, theoretical foundations, and technical methods in this field by predecessors.

3.2 Case Analysis Method：Application Scenarios of Knowledge Graphs in Intelligent Search Engines

Knowledge graphs significantly enhance the intelligence level of search engines through structured semantic networks, upgrading them from traditional keyword matching to semantic understanding and reasoning. The core application scenarios and technical implementations of knowledge graphs in intelligent search engines include:

(1) Entity Search and Knowledge Cards

When users search for specific entities (such as people, places, events), the search engine directly returns structured summaries (knowledge cards) instead of a list of traditional web page links. Map the keywords in the query to the nodes in the knowledge graph for entity linking and then extract and aggregate the key attributes of the entity from the graph (such as date of birth, occupation, achievements, etc.). For example, when searching for "Tesla" on Google, structured information such as the company's founder, stock price, and product line is displayed. The knowledge panel on the right is associated with entities such as "Elon Musk" and "SpaceX".

(2) Complex Question - Answering Systems

When answering questions that require multi-step reasoning or cross-knowledge association, use multi-hop reasoning to find paths in the knowledge graph based on graph traversal algorithms (such as BFS, reinforcement learning). Example: When searching for "The wife of the director of Avatar", the path is: Avatar → Director James Cameron → Wife Suzy Amis.

(3) Dynamic Event Search

Extract event elements in real - time from news, and track and structurally display dynamic events such as news and sports events in real - time. Identify event elements (time, place, participants) from the news, record the timestamp of the event, and analyze the event evolution. For example, for "2024 Paris Olympics schedule", automatically aggregate the competition time, venue, and medal table.

(4) Related Recommendations

Based on the semantic associations in the knowledge graph, recommend other content related to the queried entity. Calculate the similarity of entity vectors and identify strongly associated entity groups in the graph. For example, when searching for "Python", recommend related frameworks (Django, Flask) and application fields (data analysis, AI).

(5) Cross - Language Search

Unify the semantic expressions of multi - language entities, calculate the similarity of entities using multi - language word vectors, and implement multi - language knowledge graphs. For example, Wikidata provides multi-language labels for entities. Searching for "New York" and "纽约" returns the same results. Searching for "李白" and "Li Bai" is associated with the same entity.

(6) Vertical Domain Search

Integrate professional term libraries and industry databases. In professional fields such as medicine, finance, and law, knowledge graphs can provide accurate answers. For example, when searching for "Apple's market capitalization", it can automatically aggregate financial report data and stock price trends in real - time.

(7) Counterfactual Question - Answering

Answer hypothetical questions. It is necessary to combine the logical reasoning ability of the knowledge graph, model "causal edges" in the knowledge graph, and perform causal reasoning. For example: "If Steve Jobs had not returned to Apple, would the iPhone have been born?"

Table 1: Application scenarios

Search Engine	Function	Technical Highlights
Google Knowledge Graph	Entity Cards, Related Recommendations	Integration of Freebase, Multi - hop Reasoning
Baidu Zhixin	Direct Answers in Medical Search	Chinese Entity Disambiguation, Domain - specific Knowledge Graphs
Wolfram Alpha	Mathematical Formula Solving	Structured Computational Knowledge

4. Results

4.1 Key Technical Implementations of Knowledge Graphs in Intelligent Search Engines

Knowledge graphs provide semantic understanding and reasoning capabilities for intelligent search engines, upgrading them from keyword matching to intelligent question - answering and recommendation based on entities and relationships. As a structured semantic knowledge base, knowledge graphs play a core role in intelligent search engines, which can significantly improve semantic understanding ability, result relevance, and reasoning ability of searches.

(1) Knowledge Graph Construction and Storage

First, the construction of the knowledge graph is crucial. Users may wonder how to extract structured knowledge from various data sources. It is necessary to mention technologies such as entity recognition, relation extraction, attribute extraction, and also the part of data fusion, such as how to handle data conflicts from different sources. Use models such as BiLSTM + CRF and BERT to identify entities from text, and extract relationships between entities from unstructured data based on rule templates or deep - learning models. Integrate structured databases, semi - structured data, and unstructured text, resolve entity ambiguities and conflicts, and align entities using probabilistic graphical models or knowledge embeddings.

Next is knowledge storage, that is, how to efficiently store and query large - scale knowledge graphs. Use graph databases such as Neo4j and Amazon Neptune that support Cypher queries to optimize the traversal efficiency of entity relationships. For large - scale knowledge graphs, use distributed storage systems and RDF triple stores. Build inverted indexes for entity attributes and relation types to accelerate the mapping from keywords to graph nodes. Here, considering the low - latency requirements of search engines, the design of the storage structure and index optimization are very important.

(2) Semantic Understanding and Query Enhancement

Semantic representation learning, such as embedding technologies, maps entities and relationships to a vector space, which can support semantic similarity calculation and may be used for query expansion or result ranking. Models such as TransE, TransR, or more modern applications of graph neural networks are needed. Map the ambiguous words in the user's query to unique entities in the knowledge graph and disambiguate them in combination with the context. Determine the search type through a classification model and convert natural language into a structured query. In the query understanding part, traditional search engines may only perform keyword matching, but after combining with knowledge graphs, semantic parsing is required to convert the user's query into a structured query, such as SPARQL or Cypher. This involves entity linking to determine the corresponding nodes of the entities mentioned by the user in the knowledge graph, as well as intention recognition to judge whether the user wants to obtain attributes, relationships, or other information. Based on graph expansion, if a user searches for "Tesla", it is automatically expanded to related entities such as "Tesla cars" and "Elon Musk". Use knowledge embedding models such as TransE and RotatE to calculate semantic similarity, expand synonyms, and use embedding models as assistance. In terms of query expansion and ranking, knowledge graphs can help expand queries, such as through related entities or attributes, or use embedding models for semantic expansion. The result ranking may combine traditional TF - IDF and semantic relevance based on knowledge graphs, such as path analysis or embedding similarity.

(3) Search Ranking and Reasoning

In result generation and ranking, if the direct relationship is missing, complete the answer through multi - hop paths, and perform comprehensive ranking by combining traditional BM25 relevance, semantic weights of knowledge graphs, and user profiles. Then perform dynamic reasoning and completion, apply logical rules to infer implicit knowledge, use GNN models to predict missing relationships, and perform graph neural network reasoning.

Knowledge reasoning and completion are also crucial. For example, infer implicit relationships through rules or machine learning models to enrich search results. For example, when a user searches for a person's supervisor, the knowledge graph may not record it directly, but it can be found through an inference chain.

(4) Dynamic Update and Multi - modal Integration

Capture news events in real - time through a stream processing framework and update the knowledge graph. Associate entities in images and videos with text knowledge to support cross - modal search. Multi-modal data integration is also a point, such as how to process text, images, videos, etc. and associate them with the knowledge graph to support richer searches. In the part of dynamic update and maintenance, search engines need to update the knowledge graph in real - time or quasi - real - time, which requires stream processing technology and an automated verification mechanism to ensure the accuracy and timeliness of data.

Table 2: Key Technical Challenges and Solutions

Challenge	Solution
Insufficient Coverage of Long - Tail Entities	Combination of Open Extraction (OpenIE) + Crowdsourcing Completion
Lag in Dynamic Knowledge Update	Stream Data Processing (such as Kafka) + Incremental Graph Construction
Multi - modal Queries (Text + Image)	Cross - modal Alignment (CLIP Model) + Multi - modal Knowledge Graphs
Low Efficiency of Complex Reasoning	Sub - graph Sampling + Distributed Graph Computing (such as Pregel)

5. Discussion and Conclusion

Knowledge graphs, through structured semantic networks, upgrade intelligent search engines from "retrieval" to "understanding and reasoning". In the future, with the development of multi-modal technologies and causal reasoning, and the integration of knowledge graphs with large models and multi-modal technologies, knowledge graphs will further promote the intelligence of search. Knowledge graphs will further drive the transformation of search from "information retrieval" to "intelligent decision - making" and become the infrastructure of the digital age.

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A ZJ17 Cigarette-Making Machine Tobacco Stem Rate Calculation Model Based on the Improved YOLOv8

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Abstract: The traditional ZJ17 cigarette-making machine's separation technology for tobacco stems and tobacco silk relies on a wind selection device, which has problems such as low precision and poor adaptability. The high or low rate of tobacco stems in ZJ17 cigarette-making machine has a significant impact on the deviation of the single cigarette weight of the cigarette product. This paper focuses on the separation of tobacco stems and tobacco silk, and proposes an optical recognition method based on the improved RF_Yolov8n model to achieve high-precision and real-time detection of the proportion of tobacco stems and tobacco silk separation. This method mainly addresses the technical difficulties existing in the scenarios of pseudo-echo problems under high-speed motion, visual blurring issues, and small target detection in dense environments. The RF_Yolov8n model enhances the model's robustness to complex textures and artifacts by introducing the RFCBAMConv module for receptive field attention and the Faster_Block module, and further integrates features through the PAN-FPN feature pyramid network. A series of experimental results show that the mAP50 of the RF_Yolov8n model reaches 0.989, the recall rate is 0.973, and the precision is 0.971, which is significantly better than the original YOLOv8n model. The test set results show that it can accurately identify tobacco stems and tobacco silk in dense and high-speed motion scenarios, which is conducive to improving the automation level of downstream tobacco stems and tobacco silk separation, optimizing production efficiency and product quality.

Keywords. ZJ17 cigarette making machine; Yolov8n model; artifact; visual blurring; stem and shred ratio.

1 Introduction

In the cigarette manufacturing process, the deviation of the weight of each cigarette is a key indicator for assessing cigarette quality. Excessive deviation in the weight of each cigarette not only affects the physical properties and sensory quality of cigarettes but also may lead to unnecessary material waste and low equipment efficiency during production. Therefore, controlling the weight deviation of each cigarette is an important task in the cigarette manufacturing industry. The separation of tobacco stems and tobacco shreds is an important step in cigarette production, aiming to separate the tobacco stems (the thicker parts of the tobacco plant) from the tobacco shreds (the fine tobacco leaf

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fragments) to improve the quality and taste of tobacco products, which has a significant impact on the weight deviation of each cigarette.

The traditional ZJ17 cigarette-making machine uses a wind separation device for the separation of tobacco stems and tobacco shreds, as shown in Figure 1. The basic principle is to separate the tobacco stems and tobacco shreds based on their different suspension speeds in the air. However, due to the limitations of the characteristics of tobacco stems and tobacco shreds themselves, equipment status, and human errors, the traditional wind selection device usually cannot precisely adjust the wind speed and wind pressure, resulting in certain limitations in terms of accuracy, adaptability, and flexibility, and inevitably causing an increase in the deviation of single cigarette weight. Therefore, improving the tobacco stem and shred separation capability of the ZJ17 cigarette-making machine can help enhance production efficiency, ensure product quality, reduce production costs, optimize resource utilization, and ultimately improve product quality and enterprise competitiveness.

Figure 1. The equipment diagram of the ZJ17 cigarette-making machine

In recent years, With the rapid development of computer technology, the application of optical image recognition technology in the cigarette industry has become increasingly widespread [1]. The processing of cigarettes is gradually shifting from traditional methods to more refined and intelligent ones. The refined technology based on optical image recognition has attracted increasing attention due to its high accuracy and the ability to reduce the damage to the structure and composition of tobacco fibers and to lower the generation of smoke dust [2]. It has begun to be introduced into the cigarette production field. However, in the actual cigarette production, the application of optical recognition technology is still relatively lacking, and most researchers have not conducted in-depth studies on the separation of tobacco fibers under actual conditions. During the optical recognition process, the following problems urgently need to be solved: First, the problem of identifying and detecting small targets in a dense environment; second, the visual degradation of tobacco stems and fibers under high-speed movement, including high-speed motion artifacts and visual blurring caused by smoke dust particles. The actual situation of the wind separation system is shown in Figure 2.

Figure 2. The actual situation of the air separation system of the cigarette making machine

In view of this, this study aims to build an optical recognition model for addressing the motion artifacts and visual blurring issues as well as the dense distribution problem in the context of tobacco stem recognition. Object detection, as a key task in the field of computer vision, is designed to identify and locate the desired objects in images or video frames. In recent years, object detection models have been continuously evolving, mainly divided into two categories: region-based convolutional neural networks (R-CNNs) and single-stage object detection methods (such as YOLO) [3]. The region-based methods, although having higher accuracy, have relatively slower processing speeds, such as R-CNN [4], Fast_R-CNN [5], and Faster R-CNN [6]. The single-stage method directly predicts the category and position of the target through a single forward propagation, and is renowned for its speed and real-time performance. It is suitable for the identification of tobacco stems and tobacco silk under high-speed movement conditions in wind sorting devices, such as the YOLO series and SSD [7].

The YOLO series algorithms, as representatives of single-stage object detection models, have been widely used in the field of object detection since their introduction in 2016 due to their fast, accurate, and easy-to-deploy characteristic, such as YOLO [8], YOLOv2 [9], YOLOv3 [10], and YOLOv4 [11]. YOLOv8, as a version released in the past two years, has optimized the model structure, training strategy, and inference efficiency. It is particularly suitable for target detection in high-density and high-dynamic environments. Although subsequent versions such as YOLOv9 [12] and YOLOv10 [13] have been released, YOLOv8 still demonstrates strong competitiveness in terms of stable performance and small target detection. Therefore, this study selects YOLOv8 as the base model and makes improvements for the special requirements of tobacco stem and tobacco silk separation in cigarette production to achieve high-precision real-time monitoring of tobacco stems and tobacco silk, facilitating the implementation of stem content ratio monitoring and precise risk control systems, and reducing the single-stick weight deviation in the cigarette production process. The development process of the visual degradation detection model in this study is shown in Figure 3.

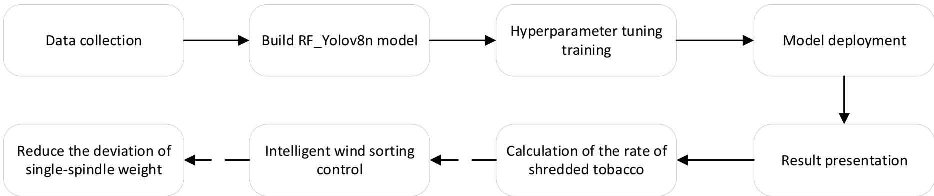

Figure 3. The development process of visual degradation detection model

2 Related works

Early research mainly focused on air separation technology, aiming to improve the separation effect by optimizing the hardware facilities of the air separation device. Xue Bai et al. [14] designed an impregnated paper strip separation system based on the combination of vacuum suspension and centrifugal air separation. Shixiu Bai et al. [15] modified the floating chamber of the ZJ17 cigarette-making unit from a straight-through type to an upward-tilted and downward-vertical type. They also added a guide plate to transform the airflow channel of the floating chamber into an "S" shape. This design enabled each bend to form different-sized vortices. Under the influence of these vortices, the mixture of tobacco stems and clumps of tobacco silk within the chamber rotated and collided, facilitating the separation of tobacco stems and clumps of tobacco silk. Zhongjun Hu et al. [16] conducted an experimental study on the influence of the height of the stem guide plate and the pressure of the small fan in the first-stage separation of ZJ17 cigarette machine on the separation effect of stems and silk. They established relevant models and indicated that the pressure of the small fan was positively correlated with the content of stems in the cigarette rods. Lanbo Liu et al. [17] improved the air separation chamber of the PROTOS70 cigarette-making machine by integrating a stem scattering mechanism, which added the lifting channels for tobacco stems and shreds, allowing the tobacco shreds to rise and swing simultaneously. By adjusting the air separation pressure, the stems and shreds were separated, further enhancing the separation effect. Zhaohui Lin et al. [18] changed the tobacco shred feeding pipe of the secondary separation device to an "S" shape, improving the separation efficiency. Haotian Zhang et al. [19] compared the circular and square flotation chambers and set up a secondary centrifugal air separation to optimize the separation efficiency. Xinhu Zheng [20] designed an external secondary separation device for the ZJ17 cigarette-making machine by comprehensively applying vacuum suspension separation technology and centrifugal separation technology. However, none of the above studies have solved the problem of the outdated fixed-position manual airspeed adjustment method, which causes significant errors due to human factors.

With the increasingly widespread application of optical image recognition technology in the cigarette industry, the refined technologies based on optical image recognition have gradually attracted the attention of researchers. Kewen Zhao et al. [21] measured the uniformity of tobacco shred blending based on near-infrared spectroscopy technology. By collecting the near-infrared spectral information of samples and determining the indicator values, they established a system for evaluating the uniformity of tobacco shred, tobacco stem, and reconstituted tobacco shred blending using pattern recognition and calibration models. Yaping Zhang et al. [22] studied the determination method of tobacco shred blending uniformity based on thermal analysis technology. This method is simple to operate, has high precision, and good repeatability, and is suitable for the accurate determination of tobacco shred blending uniformity. Fazhan Tao et al. [23] established a rapid recognition model for stem shred impurities in tobacco shreds using hyperspectral imaging technology combined with machine learning, achieving the identification of stem shreds with diameters of 1.0-1.5 cm, 0.5-1.0 cm, and <0.5 cm. Xiaoteng Kou [24] measured the RGB mean values of tobacco stems and shreds using image analysis technology. Through regression analysis of the stem shred ratio and RGB mean values, a function model of the stem shred blending ratio and RGB mean values was obtained. D Wang et al. [25] proposed a method for identifying and locating the stem of tobacco leaves based on 3D stereo vision. By using stereo vision technology to construct depth information and combining image processing with deep learning techniques, the segmentation and 3D positioning of the tobacco stem area were achieved. This method achieved an identification accuracy rate of over 98% in complex backgrounds, and the positioning error was controlled within millimeters. Lei Cheng [26] designed a tobacco stem sorting control system based on spectral and image fusion, which can effectively improve the efficiency and accuracy of tobacco stem impurity removal and meet the needs of industrial production. Wenchao Shen [27] proposed an inter-class standard deviation recognition algorithm based on color features and an inorganic foreign matter recognition algorithm combining SVDD with lookup table, which achieved an accuracy of over 95% for tobacco inorganic foreign matter recognition.

In conclusion, although the wind selection technology remains the core process for separating tobacco stems from tobacco silk, the combined wind selection technology integrating optical technology is gradually demonstrating great potential. However, there are numerous image recognition algorithms at present, but their application in the actual production of cigarettes is still relatively scarce, and most researchers have not conducted studies specifically on the separation of tobacco stems under actual conditions. This research selects YOLOv8 as the basic model and improves it to meet the special requirements of tobacco stem and tobacco silk separation in cigarette production, in order to achieve high-precision real-time monitoring of tobacco stems and tobacco silk. Specifically, this research improves the backbone network of YOLOv8, introduces the receptive field attention RFCBAMConv module and the Faster_Block module from FasterNet, and through the attention convolution module and the deep feature extraction structure, the adjusted model can better discover and capture the deep information of the image, further solving the problem of low accuracy caused by visual degradation such as motion artifacts and visual blurring. In addition, this research also verifies the improved model's ability to solve target detection in high-speed moving environments through comparison, ablation, and visualization experiments, fully demonstrating its possibility for future use in building an intelligent optical selection system for tobacco stem and tobacco silk separation and achieving precise real-time control of wind speed.

3 Materials and Methods

3.1 Experimental Platform

The experiments in this paper were conducted under the Windows 11 system. The hardware configuration used was an Intel i5 12600 processor with a frequency of 3.7 GHz, 32GB of memory, a Nvidia GeForce RTX 4060Ti graphics card, and 16GB of GPU video memory. The software used was Pycharm IDE, and the Pytorch [28] deep learning framework was adopted. Python 3 was used as the programming language for the training and testing of the network. The camera selected was the Microvision NX series camera. It is a high-speed industrial camera with a body size of 28×28×75mm. The small size is suitable for deployment in the second-stage air separation mechanism of the ZJ17 cigarette machine, and its shooting resolution can reach up to 4608*3288, with a maximum frame rate of approximately 7fps under a resolution of 4608*3288, which is suitable for image acquisition of the mixture of tobacco stems and shreds with small targets and high-speed movement. The construction process of the monitoring model for the air separation system's filament rate is shown in Figure 4.

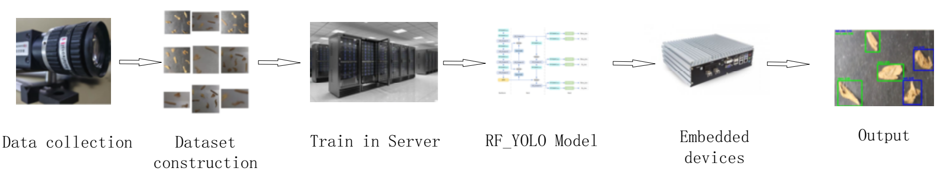

Figure 4. The flowchart of the monitoring model construction for the stem and shred Rate of the Wind Selection System

3.2 Dataset Preparation

This study focuses on the target detection of stem and shred in the stem and shred separation operation process of the ZJ17 cigarette making machine. Samples were collected from the cigarette making machine in the actual production line, and the Microvision camera was used to obtain the dataset of stem and shred. The dataset included 276 annotated static images of mixed stem and shred and 30 annotated dynamic images. The steps for dataset preparation are as follows:

1) With the help of the cigarette factory, this study collected stem and shred samples from the wind selection device of the ZJ17 cigarette making machine. Professionals separated the two types of samples and randomly selected the same number of samples from each category. The samples were randomly grouped and placed on the transmission device, and the transmission device simulated high-speed motion and used the Microvision camera to obtain the dataset DLS with visual degradation.

2) Professional image annotation tools such as LabelImg were used to annotate the collected images. Professionals annotated the stem and shred in the images, corresponding to the categories "stem" and "leaf" respectively. The annotation information included the position (bounding box) of the target and the category. The image examples of the dataset are shown in Figure 5, where the "stem" category is annotated with a green box and the "leaf" category is annotated with a blue box.

3) Check the image data, delete damaged images and distorted images, and ensure that all images have the same format.

4) Resize all images to a unified image size of 640*640 to meet the input requirements of the model. Normalize the image data to make the pixel values between 0 and 1.

5) Data set partitioning and data augmentation: The data set is randomly divided into training set, validation set and test set in a ratio of 7:2:1. The training set and validation set are subjected to random Gaussian blurring to enhance sample diversity. The Gaussian kernel size is divided into five levels from 1 to 151. Five different degrees of visual blurring scenarios are simulated for the test set, corresponding to five degrees of visual degradation environments in the working conditions. The visual blurring degree levels are classified from level one to level five, which are used to test the robustness of the model under different degrees of visual degradation in the subsequent process. The augmented data set is saved in the corresponding folders for subsequent model training and testing.

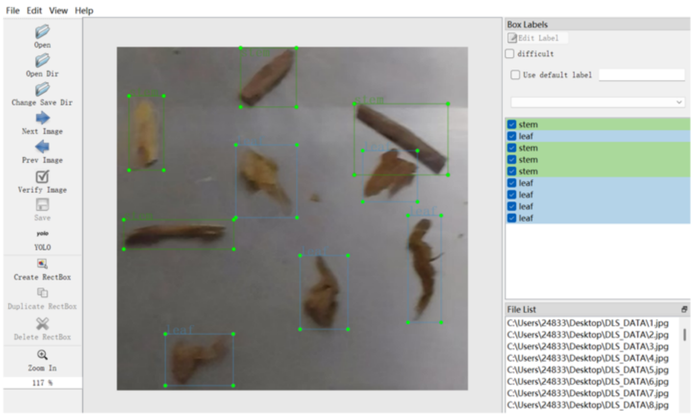

Figure 5. The example images of the Dataset

3.3 Model Fine-tuning

This study is based on the Yolov8n [29] model. To address the problem of identifying tobacco stems and shreds in high-speed moving environments, we have made improvements to the backbone part of the model. Specifically, by introducing the RFCBAMConv module with receptive field attention to optimize the original convolution structure, and replaced the bottleneck structure with the FasterBlock module from the FasterNet architecture. Through leveraging the attention mechanism effect of the RFCBAMConv module and the advantages of FasterBlock in efficient feature extraction and deep information aggregation, this work overcomes the problems of motion artifacts and visual blurring in high-speed motion scenarios, and makes breakthrough explorations and optimizations in the detection of small targets. These improvements provide a new optical image solution for engineering problems in actual scenarios of tobacco stem target detection.

The overall structure is divided into three main parts: Backbone, Neck, and Head, as shown in Figure 6.

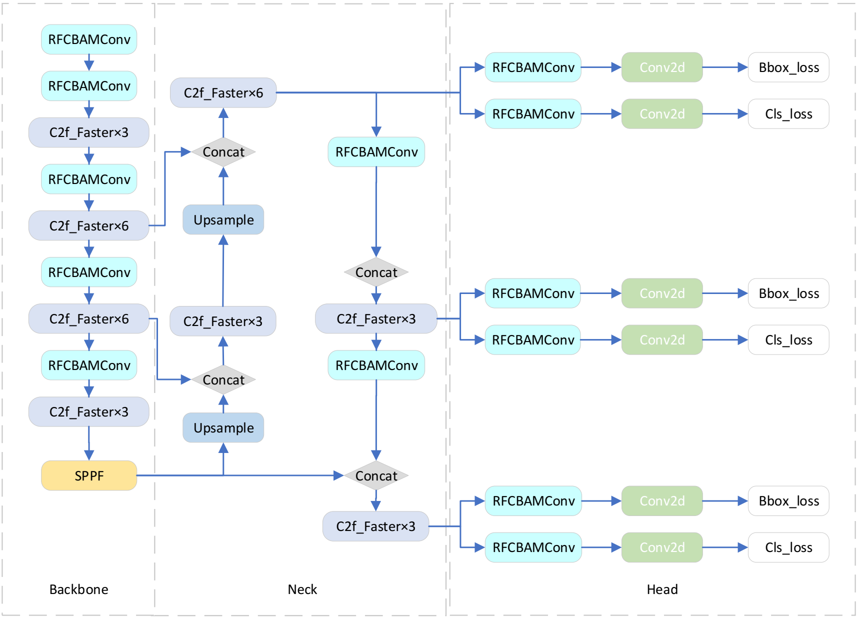

Figure 6. The framework diagram of RF_Yolov8n object detection model

The backbone part of the model mainly extracts the basic features of the image through the RFCBAMConv module and C2F_Faster modules, performs multiple downsampling operations, and generates multi-scale feature maps to provide rich representation information for subsequent detection tasks.

To enhance the model's ability to capture the details of tobacco stems and tobacco shreds in complex backgrounds, the backbone part introduces the RFCBAMConv [30] module with receptive field attention, which combines CBAM [31] (Convolutional Block Attention Module) and radial field perception mechanism. As shown in Figure 7, its core idea is to introduce an adaptive adjustment mechanism of the radial field on top of the traditional convolution kernel to simulate the attention process of the biological visual system when observing objects. Specifically, RFCBAMConv achieves more refined feature expression through dynamic adjustment of the receptive field and the dual attention mechanism of space and channel. On one hand, the radial field transformation enhances the perception ability of the convolution kernel for local details, especially the complex textures of tobacco stems and tobacco shreds, enabling the model to accurately distinguish between them; on the other hand, the CBAM module learns the spatial attention map and channel attention map to achieve weighted focusing on different regions and channels features, allowing each channel to allocate different attention levels based on its importance in target detection, thereby integrating global and local information in the feature extraction stage and improving the discrimination ability of the model. Compared with traditional convolution operations, RFCBAMConv can effectively suppress visual degradation interference and improve the robustness of the model in complex image backgrounds. Secondly, its adjustable receptive field characteristic enables the model to maintain high detection accuracy while having good detail adaptability, significantly reducing missed detections and false detections. More importantly, RFCBAMConv optimizes the overall computational efficiency while improving detection performance, providing feasible technical support for real-time detection of the mixed rate of tobacco stems and tobacco veins in large-scale wind selection systems.

The C2F_Faster structure is shown in Figure 8. In this part, the FasterBlock module from the FasterNet [32] network architecture is used to replace the Bottleneck module in the original C2f for feature extraction. The FasterBlock combines partial convolution (PConv) and point-wise convolution (PWConv), and has stronger feature extraction and spatial information expression capabilities, which helps to improve detection accuracy and reduce false alarms and missed detections. Moreover, this module can significantly improve the overall computational efficiency without increasing the computational complexity by reducing redundant computations and memory access overheads. This enables the model to achieve faster running speed while maintaining accuracy. For image target detection in high-speed motion environments with artifact problems, FasterBlock can better optimize the feature extraction process due to its efficient information aggregation ability, thereby enhancing the stability and accuracy of the model in complex scenarios.

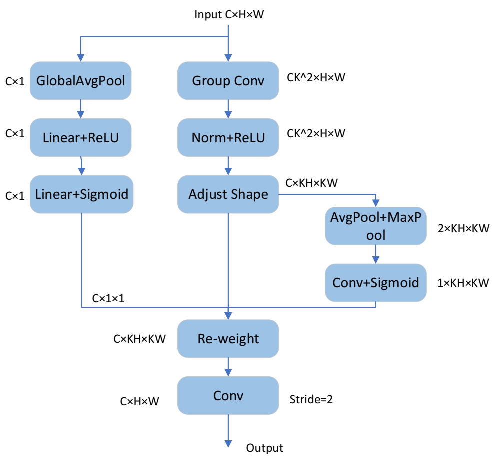

Figure 7. The RFCBAMConv structure diagram

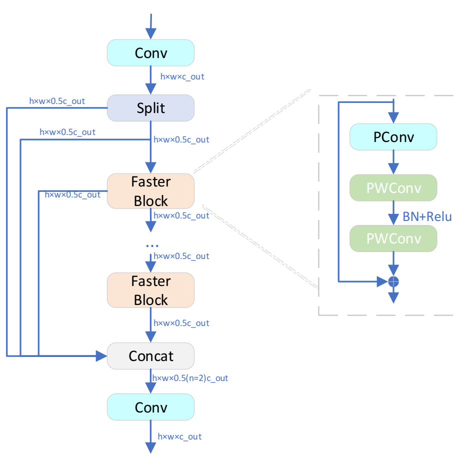

Figure 8. The G2f_Faster structure diagram

The Neck section is designed to further integrate the features extracted by the backbone module to enhance the semantic information of feature representations. In this part, the concept of feature merging is adopted to merge feature maps of different scales. The PAN-FPN structure is used as the feature pyramid network, integrating the bottom-up path enhancement of PAN [33] and the top-down path propagation mechanism of FPN [34]. Through the top-down feature transfer and bottom-up feature aggregation, the feature extraction ability of the model is enhanced. This structure not only retains the semantic information at the high level but also supplements the positioning information at the low level, making the network more comprehensive and accurate when dealing with multi-scale targets. Specifically, the neck performs two rounds of up-sampling and concatenation, merging the low-resolution, high-semantic feature maps with the high-resolution, low-semantic feature maps to generate multi-scale and multi-level feature maps. This feature fusion strategy takes into accounts both positioning information and semantic information, enabling the model to have stronger discriminative ability when facing multi-scale3 targets and improving the model's perception ability for the complex shapes of tobacco stems and tobacco filaments.

The head serves as the output module of the model, responsible for the final target detection and classification. Each Head corresponds to a specific scale of the feature map, and internally contains two branches: one for bounding box regression and the other for class prediction. This design ensures that the model can accurately capture and recognize various-sized targets by conducting independent detection operations on different-scale feature maps. This model can accurately identify and classify tobacco stems and tobacco filaments of different sizes and shapes through multi-scale feature fusion and detection, and is suitable for industrial applications in complex background scenarios [35]. The multi-scale detection mechanism designed in this way can ensure the model's high flexibility and accuracy in practical applications.

3.4 Evaluation Metrics

To comprehensively evaluate the performance of the model, this study mainly adopts mean average precision(mAP), Recall (R), and Precision (P) as evaluation metrics, and their calculation formulas are as follows:

$$\mathrm{mAP} = \frac{1}{k}\sum_{i=1}^{k} APi \tag{1}$$

$$\mathrm{R} = \frac{TP}{TP+FN} \tag{2}$$

$$\mathrm{P} = \frac{TP}{TP+FP} \tag{3}$$

In the formula: APi represents the average precision of the i-th type of detection target, which is the area under the P-R curve; TP represents the number of positive samples predicted as positive samples, that is, the number of correct detections of tobacco stems and tobacco shreds; FP represents the number of negative samples misjudged as positive samples, that is, the number of detection targets with classification errors; FN represents the number of positive samples wrongly predicted as negative samples, that is, the number of missed detections.

4 Experimental Results and Analysis

4.1 Comparative Experiment

In order to select appropriate parameters for model training, this study conducted a comparative experiment by setting different batch sizes (B=8, 16, 24) and different optimizers (O=SGD, Adam) for the model, and evaluated the parameters based on mAP50, Recall, and Precision as the evaluation indicators. The training results showed that the best parameters were a batch size of 8 and an optimizer of Adam, with corresponding mAP50, Recall, and Precision values of 0.745, 0.65, and 0.738 respectively. The results of the comparative experiment are shown in Table 1. Based on this, through setting different training cycles, a series of adjustments and tests were conducted on the number of training batches. The range of the number of training batches was from 50 to 350, increasing by 25 in each step, forming a complete test sequence. In this way, a comprehensive comparative analysis of the model performance under different numbers of training batches was carried out to find the batch configuration that could achieve the best training effect. The comparison test results are shown in Figure 9. These training results show that as the number of training batches increases, the evaluation indicators show an upward trend. The peak is reached when the number of training epoch is 300, and thereafter, as the number of epochs increases, the indicators basically remain unchanged. Therefore, the optimal number of training epoch is 300, and the corresponding evaluation indicators of the model are mAP50, Recall, and Precision of 0.989, 0.973, and 0.971 respectively, showing good performance.

Table 1. The comparative experiment results of batch size and optimizer

E=50	mAP50	Recall	Precision
B=8，O=SGD	0.597	0.554	0.563
B=16，O=SGD	0.653	0,620	0.573
B=24，O=SGD	0.645	0.600	0.610
B=8，O= Adam	0.745	0.65	0.738
B=16，O= Adam	0.714	0.529	0.783
B=24，O= Adam	0.737	0.719	0.622

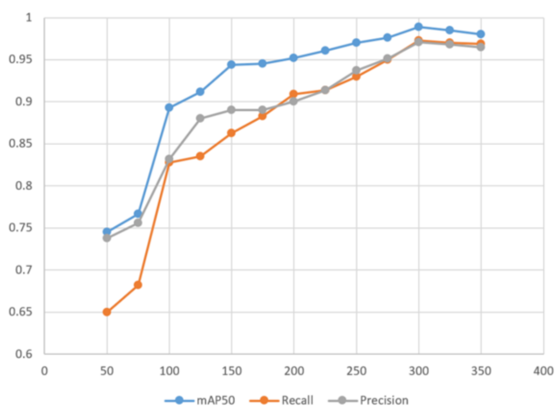

Figure 9. The line chart of comparison test results over epochs

4.2 Model Performance Evaluation

Through comparative experiments, Adam optimizer was ultimately selected. The learning rate was set at 0.01, batch size was set at 8, and epoch was set at 300. The loss curves of the training set and validation set during the training process are shown in Figure 10.

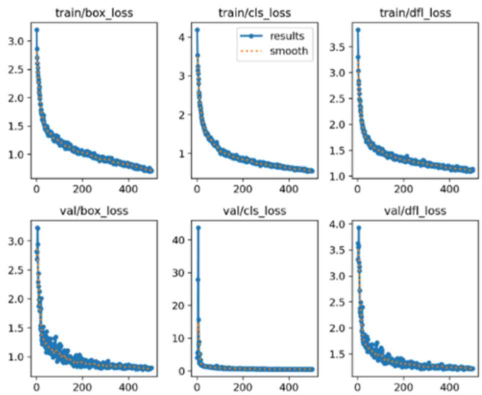

Figure 10. The loss curves of training and validation sets

Figure 10 shows three subplots on each side, from left to right, corresponding to the bounding box loss, classification loss, and focus distribution loss of the training set and validation set respectively. In terms of the overall trend, the loss values of each loss function show a decreasing and converging trend, indicating that the model gradually improves in the tasks of bounding box prediction, classification, and handling of data class imbalance, and the model training status is good, without showing an overfitting trend.

For the visual degradation scene dataset, in order to obtain the most suitable confidence threshold to optimize the performance of the model, this study obtains the best confidence threshold of the model by analyzing the F1 score curve during the training process. The F1 score curve is shown in Figure 11. From the F1 curve, it can be seen that as the confidence increases, the F1 score first rises and then drops. For the "stem" category, the F1 score reaches its peak at a confidence of 0.481, and for the "leaf" category, the F1 score reaches its peak at a confidence of 0.476. Overall, the F1 score of all categories reaches its best at 0.479, which is 0.96. The F1 score curves corresponding to "stem", "leaf", and "all classes" have basically the same shape trend. The F1 score curve of "stem" is slightly higher than the other two, indicating that the overall model's performance is basically consistent in each category, and the training effect of the "stem" category is slightly better than that of the "leaf" category.

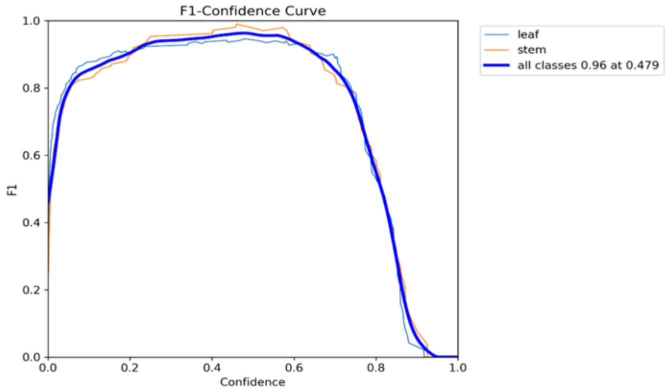

Figure 11. Confidence-F1 score curve

Figure 12 shows the trend of Precision, Recall, mAP50, and mAP50-95 of the model during the training process. Specifically, the upper part of Figure 12 displays the curves of accuracy and recall rate, while the lower part shows the changes in mAP50 and mAP50-95 values. As the training progresses, both Precision and Recall rate show a continuous upward trend, eventually stabilizing at approximately 0.971 and 0.973 respectively. This result indicates that the model performs well in reducing false alarms and effectively capturing positive samples, demonstrating high accuracy and reliability. The values of mAP50 and mAP50-95 also continue to increase with the training process, eventually stabilizing at approximately 0.989 and 0.791 respectively. The mAP is an important metric for evaluating the performance of object detection models, where mAP50 represents the average precision at an IoU (Intersection over Union) threshold of 0.5, and mAP50-95 represents the average precision within the range of IoU thresholds from 0.5 to 0.95 (with a step size of 0.05). The relatively high values of both indicators indicate that the model has high detection performance across different IoU thresholds and can effectively distinguish between target samples such as tobacco stems and tobacco shreds.

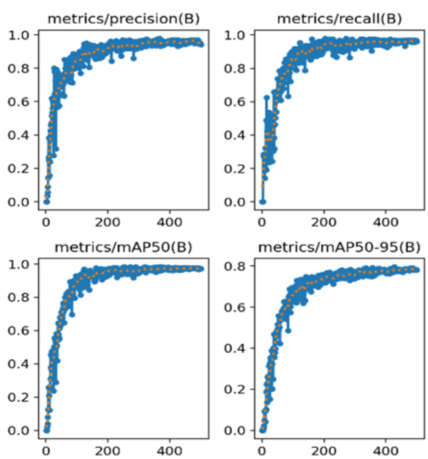

Figure 12. The training curve of evaluation metrics

Figure 13 shows the relationship curve of precision-recall during the training process. From the figure, it can be seen that for the "leaf" category, the average precision rate is 0.967; for the "stem" category, the curve is slightly higher than that of the "leaf" category, with an average precision rate of 0.974; the average precision rate of the model across all categories (mAP50) is 0.970. Overall, the precision and recall rates in most areas remain at a high level, close to 1, indicating that the overall performance of the model in different categories is good.

The confidence-Recall relationship curve is used to evaluate the performance of the classification model under different confidence thresholds. The model training curve is shown in Figure 14. As can be seen from the figure, at low confidence levels, the model's recall rate is close to 1, indicating a high recall rate and suggesting that the model performs well in capturing positive samples and effectively reduces false negatives. As the confidence level increases, the recall rate gradually decreases, but the overall performance of all categories is similar to that of individual categories, indicating that the model's performance is relatively consistent across different categories, without significant category preferences or performance differences. Between high confidence levels of 0.7 and 0.8, the overall recall rate of the model remains between 0.6 and 0.8, showing the model's robustness in capturing positive samples.

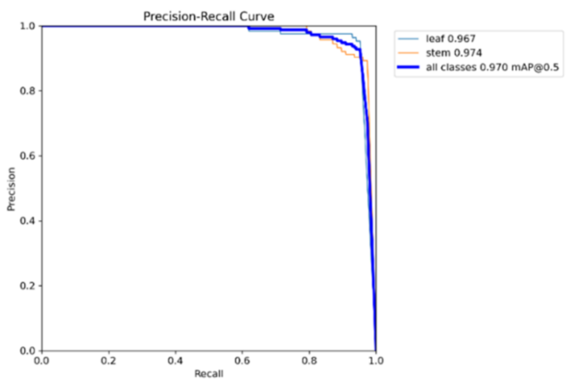

Figure 13. Precision-Recall relationship curve chart

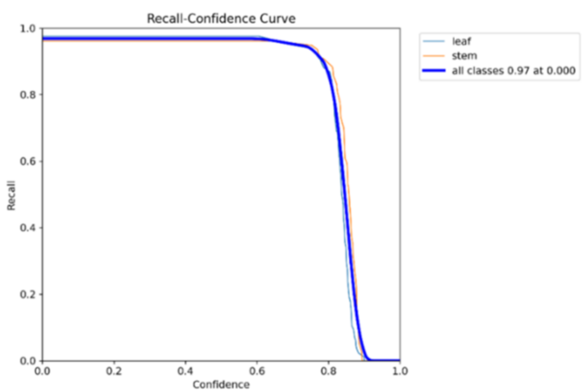

Figure 14. Confidence-Recall relationship curve chart

The confidence-precision relationship curve chart is shown in Figure 15. As the confidence increases, the precision rate shows an upward trend. The right-tailed statistics indicate that the precision rate of all categories reaches 1.00 when the confidence is 0.731, meaning that the model's predictions for all categories are correct under this confidence level. The model can maintain a relatively high precision rate in most confidence ranges, further verifying that the overall performance of the model is good, with good generalization ability and robustness, and is suitable for scenarios where high-precision prediction of cigarette shred rate is required.

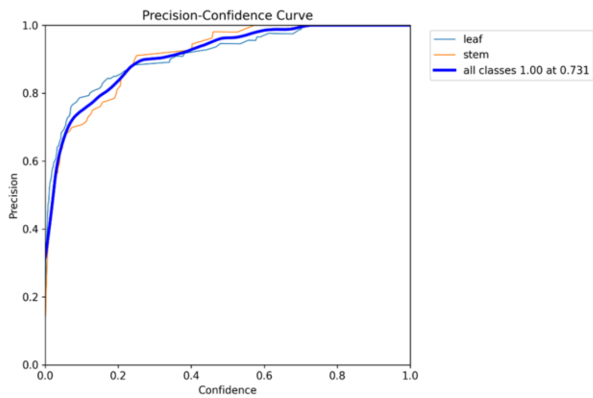

Figure 15. Confidence-Precision relationship curve chart

To reflect the specific performance of the model in the classification of tobacco stems and shreds, this study drew a confusion matrix to reflect the actual target detection ability of the trained model. The confusion matrix is shown in Figure 16. Figure 16 shows that the actual category is "leaf", that is, a large part of the tobacco shreds can be correctly classified, accounting for 96.39%; Actually, it is "stem", that is, a large part of the images of tobacco stems can also be correctly classified, accounting for 97.62%. Overall, the model performs well in the classification of "tobacco stems" and "tobacco shreds".

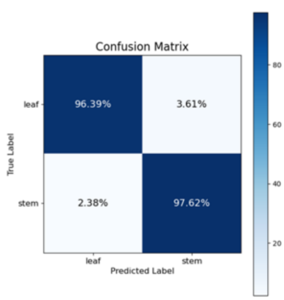

Figure 16. Confusion Matrix

4.3 Ablation Experiments

To verify the effectiveness of the introduced modules in this study, ablation experiments were conducted on the original Yolov8n model and the improved new model RF_Yolov8n. The results are shown in Table 2. As can be seen from the table, after introducing the RFCBAMConv convolution with receptive field attention and the Faster_Block module, the evaluation indicators of the model have all improved, It fully demonstrates the accuracy of the improved model in the target detection of visual-degraded tobacco stems and tobacco filaments.

Table 2. Ablation Experiment Results Table

E=300,B=8,O=Adam	mAP50	Recall	Precision
Yolov8n	0.849	0.773	0.816
RF_Yolov8n	0.989（+16.43%）	0.973（+25.98%）	0.971（+18.77%）

4.4 Visualization Analysis

To verify the robustness of the model under different degrees of visual degradation scenarios, this study conducted tests on datasets with different degrees of visual degradation. Figure 17 shows the visualization results of the model under different degrees of visual degradation scenarios. Additionally, this study evaluated the performance of the model under different degrees of visual degradation using mAP50, Recall, and Precision as evaluation indicators. The final results are shown in Figure 18, where the horizontal axis represents different degrees of visual degradation, and the vertical axis represents the corresponding values of each indicator. Figures 17(a) to (f) represent six different degrees of visual degradation, corresponding to artifact-like visual degradation under working conditions and five different degrees of visual blurring applied on this basis. Each sub-figure on the left shows the visualization results of the true labels of the images, including the labels of the targets and the bounding box information, while each sub-figure on the right shows the visualization results of the predicted labels of the model, including the labels of the predicted targets and the corresponding confidence and bounding box information. In addition, the upper left corner of each prediction visualization result shows the corresponding display of the proportion of tobacco stems and tobacco leaves. Figures 17(a) to (f) show that the model has consistent detection effects on these six degrees of visual degradation and the prediction results match the actual results of the original images, performing well. However, the drawback is that as the degree of visual degradation increases, the confidence of the model in detecting the target decreases. Nevertheless, as shown in Figure 18, when the degradation level reaches level five, the model still has good performance. In the three-level degradation environment, human eyes cannot recognize it anymore. Therefore, the model can adapt to the industrial production environment as a whole.

In conclusion, it can be seen that this model performs poorly in handling visual degradation effects of a high degree, but performs well in handling visual degradation effects of a low degree and a medium degree. The model can effectively handle most cases of visual degradation problems and meet the requirements of the development of the cigarette production industry. It provides high-precision stem content data for wind selection equipment.

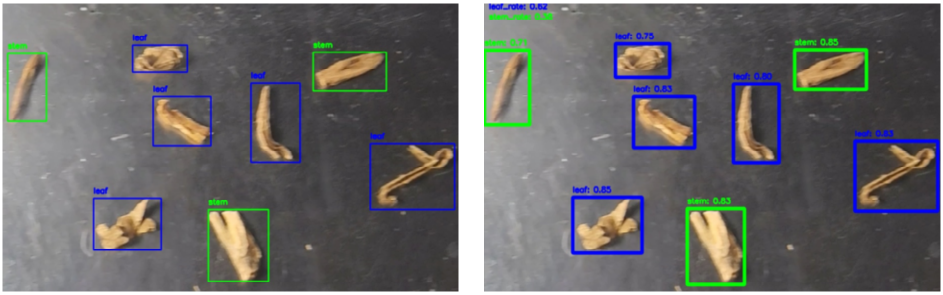

Figure 17 (a). The comparison chart of the prediction results before and after for artifact model

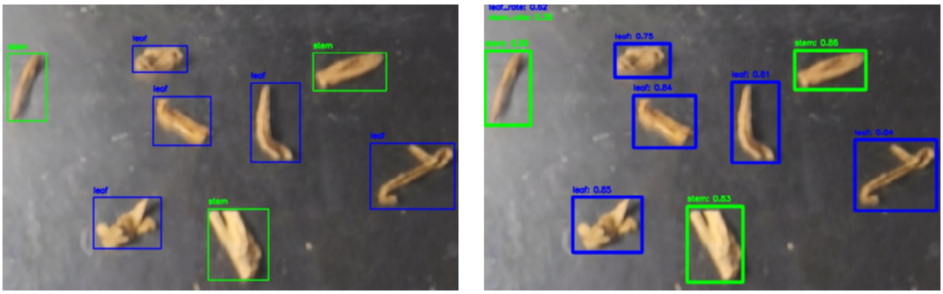

Figure 17(b). The comparison chart of prediction results before and after correction for artifacts and first-level blurring model

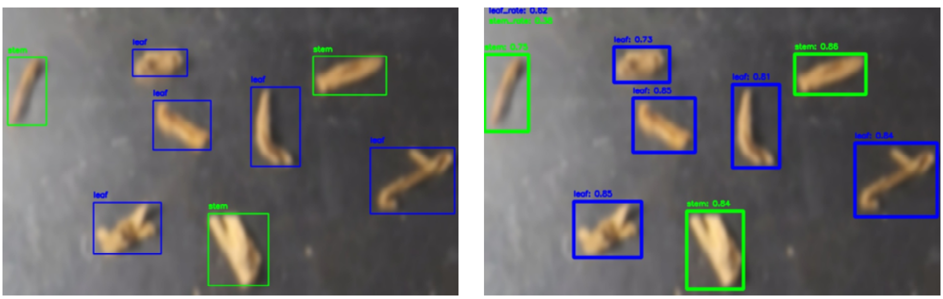

Figure 17(c). The comparison chart of prediction results before and after correction for artifacts and second-level Blurring Model

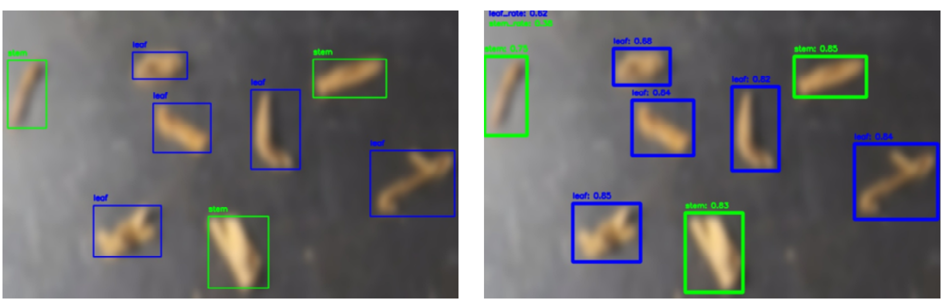

Figure 17(d). The comparison chart of prediction results before and after correction for artifacts and third-level Blurring Model

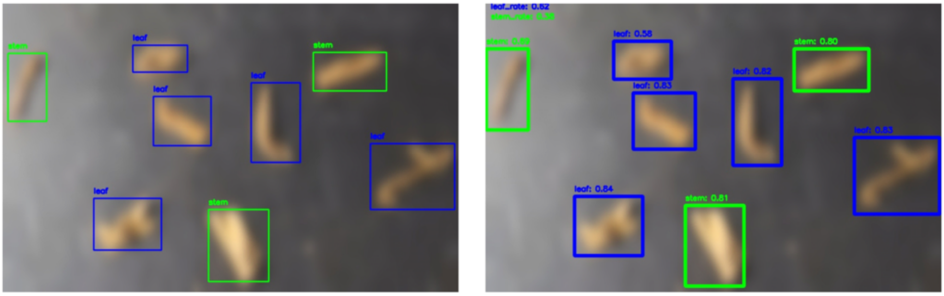

Figure 17(e). The comparison chart of prediction results before and after correction for artifacts and fourth-level Blurring Model

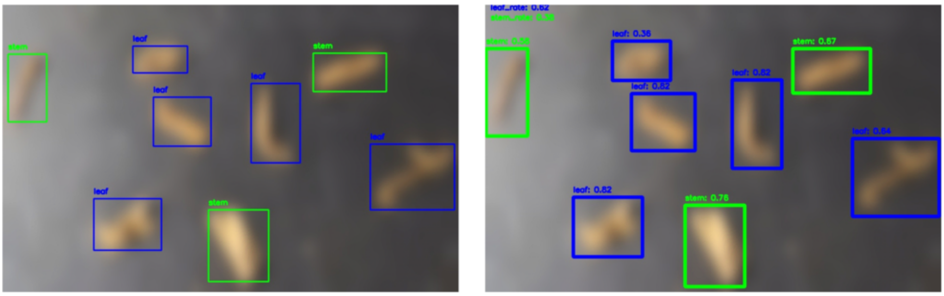

Figure 17(f). The comparison chart of prediction results before and after correction for artifacts and fifth-level Blurring Model

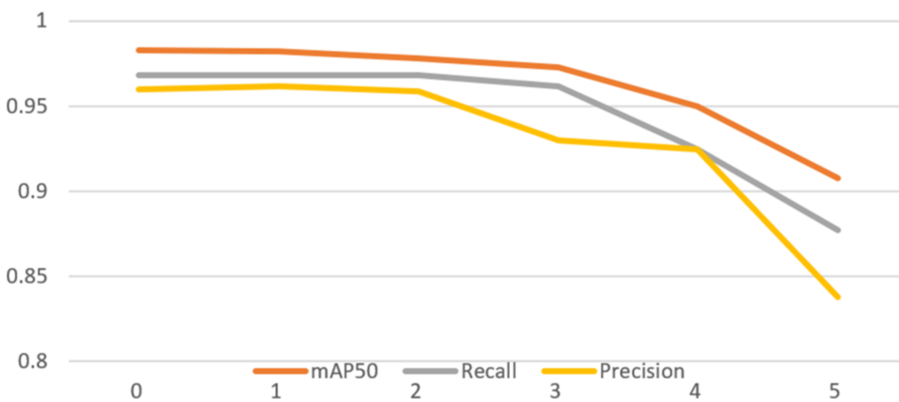

Figure 18. The line chart for model performance evaluation under different degrees of visual degradation

5. Conclusion

In this study, the improved RF_Yolov8n model was utilized for the classification and detection of tobacco stems and tobacco shreds, achieving remarkable results. The overall mAP50 value of the model was 0.989, with a recall rate of 0.973 and an precision rate of 0.971. This indicates that the model has high detection performance under different confidence threshold values. Specifically, the detection accuracy for tobacco stems and tobacco shreds was 0.967 and 0.974 respectively, and the recall rates were 0.997 and

0.946 respectively. The detection performance for tobacco stems and tobacco shreds was close to the ideal level. This model effectively improved the ability to discover and fuse multi-scale features by introducing the RFCBAMConv module for attention to receptive field and the Faster_Block feature extraction module, combined with the PAN-FPN feature pyramid network. It can accurately identify small targets even in dense environments and high-speed moving conditions.

Furthermore, the loss functions in the training process of the model gradually decreased with the increase in the number of iterations, indicating a gradual optimization in target boundary positioning, classification, and prediction of target distribution. Through visual comparison of the detection results, the model's prediction results were highly consistent with the original annotations, demonstrating the reliability and accuracy of the model in practical applications. Overall, the advantages of the RF_Yolov8n model in precise detection of small targets, multi-scale, and high-speed moving complex environments in the tobacco industry have important practical significance. It provides model support for the detection of stem-shred mixture ratio and helps improve the automation level of tobacco stem and tobacco shred separation, as well as production efficiency and product quality. The future research focus will be on establishing an intelligent wind sorting system control device based on this study, achieving real-time monitoring of the stem-shred mixture ratio, precisely controlling the wind speed of the wind sorting system to complete high-quality cigarette raw material supply, and promoting the control of single cigarette weight deviation.

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The Profile-Ridge-Type Estimator in Partially Linear Varying-Coefficient Model

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Abstract. This paper addresses the issue of biased estimation in a partially linear varying-coefficient model when multicollinearity is present in the linear parametric component of the regression model. We introduce a new estimator for the linear parametric part and discuss its properties. Finally, we demonstrate the theoretical findings through a simulation analysis by R.

Keywords. Profile-ridge-type estimator, Multicollinearity, Partially linear varying-coefficient model

1. Introduction

Consider the following model:

$$Y_i = X_i'\beta + Z_i'\alpha(T_i) + e_i, i = 1, ..., n \tag{1}$$

$X_i = (X_{i1}, ..., X_{ip})'$ defines the design matrix with dimension $p \times 1$, $Z_i = (Z_{i1}, ..., Z_{iq})'$ shows the design matrix with dimension $q \times 1$, $\beta_{p\times 1}$ is the unknown coefficient, $\alpha(\cdot) = (\alpha_1(\cdot), ..., \alpha_q(\cdot))'$ shows the unknown vector with $q \times 1$, T_i is a single variable, Y_i is the dependent variable, $E(e_i|X_i, Z_i, T_i) = 0$ (Wei and Wu, [1]) and $Var(e_i|X_i, Z_i, T_i) = \sigma^2$,where $\sigma^2 > 0$ is the unknown parameter.

This paper primarily discusses the parameter estimation of β. Many authors have studied parameter estimation in (1). For instance, Fan and Huang [2] introduced the local linear estimation for the parametric component and discussed the properties of this estimator. Wei and Wu [1] presented the backfitting estimation for the parametric part.

In practical data analysis, multicollinearity issues are frequently encountered when building regression models. It is well-known that even though the least squares estimate remains the minimum variance unbiased linear estimator in theory, in the presence of multicollinearity, the following problems can occur: (1)The regression coefficients or their standard errors become abnormally large. (2) The signs of the estimated regression coefficients may be opposite to their practical meanings. To address the issues caused by multicollinearity, several biased estimation methods have been proposed as alternatives to ordinary least squares estimation. These methods aim to provide more stable and re-

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liable estimates in the presence of multicollinearity. Examples of such biased estimators include principal component regression [3]. the ridge estimation [4], the Liu estimator [5], the modified ridge estimator [6], the stochastic mixed ridge estimator [7], the two parameter mixed estimator [8], the mixed Kibria-Lukman estimator [9].

Due to the presence of the linear parametric part in model (1), multicollinearity issues can also arise in practical data analysis. Therefore, we need to discuss how to handle multicollinearity in model (1). Wei [10] introduced ridge estimation in model (1) to address multicollinearity. Li and Li [11], Zhang [12], proposed the weighted mixed profile Liu estimation for model (1) to overcome multicollinearity.

This paper also discusses how to estimate the linear parameters in model (1) when multicollinearity is present. We propose a new biased estimator called the profile ridge estimator for the linear parametric component in model (1). Lastly, we consider the properties of the new estimator.

2. The proposed estimator

2.1. The Profile least squares estimator

For the parametric estimator of β, we use the local linear estimator proposed by Fan and Huang [2]. First, we apply the Taylor expansion to $\{\alpha_j(\cdot), j=1,...,q\}$. Any point in the given t field, we have

$$\alpha_j(T_i) \approx \alpha_j(t) + \alpha_j'(T_i)(T_i - t) =: a_j + b_j(T_i - t), j = 1,...,q \tag{2}$$

For the given parametric vector β, minimization

$$\sum_{i=1}^{n} \{Y_i - X_i'\beta - Z_i'(A + H(T_i - t))\}^2 N_h(T_i - t) \tag{3}$$

then we get the estimator of $\alpha(t)$, where $A = (A_1,...,A_q)'$, $H = (H_1,...,H_q)'$, $K_h(.) = K(./h)/h$. Let $X = (X_1,...,X_n)'$, $Z = (Z_1,...,Z_n)'$,$Y = (Y_1,...,Y_n)'$,$\varepsilon = (\varepsilon_1,...,\varepsilon_n)'$, $\Delta_t = diag(N_h(T_1 - t),...,N_h(T_n - t))$ and

$$D_t = \begin{pmatrix} Z_1' & \frac{T_1 - t}{h} Z_1' \\ \vdots & \vdots \\ Z_n' & \frac{T_n - t}{h} Z_n' \end{pmatrix}, M_t = \begin{pmatrix} Z_1'\alpha(T_1) \\ \vdots \\ Z_n'\alpha(T_n) \end{pmatrix} \tag{4}$$

Then we can rewritten model (1) as

$$Y - X\beta = M + e \tag{5}$$

Thus we can get the estimator of $\alpha(t)$

$$\hat{\alpha}(t,\beta) = (I_q\ 0_q)\{D_t'\Delta_t D_t\}^{-1} D_t'\Delta_t (Y - X\beta) \tag{6}$$

Then we can get the estimator of M, which is given as follows:

$$\hat{M} = \begin{pmatrix} (Z_1' \ \ 0)\{D_{T_1}'\Delta_{T_1}D_{T_1}\}^{-1}D_{T_1}'\Delta_{T_1} \\ (Z_2' \ \ 0)\{D_{T_2}'\Delta_{T_2}D_{T_2}\}^{-1}D_{T_2}'\Delta_{T_2} \\ \vdots \\ (Z_n' \ \ 0)\{D_{T_n}'\Delta_{T_n}D_{T_n}\}^{-1}D_{T_n}'\Delta_{T_n} \end{pmatrix}(Y - X\beta) =: U(Y - X\beta) \tag{7}$$

Then set $\hat{M}$ into (5), we can get

$$\tilde{Y} = B\beta + \varepsilon \tag{8}$$

where $\tilde{Y} = (I-U)Y$, $B = (I-U)X$, $\tilde{M} = (I-U)M$. Then we can get the Profile least squares estimator:

$$\hat{\beta}_{PE} = (B'B)^{-1}B'\tilde{Y} \tag{9}$$

In practice, when the linear parametric part exist multicollinearity, Wei [10] proposed Profile-ridge estimator to discuss this problem, which is give as follows:

$$\hat{\beta}_{PRE}(k) = (B'B + kI)^{-1}B'\tilde{Y} \tag{10}$$

where $k > 0$.

2.2. The Profile-ridge-type estimator

In this subsection we will introduce the new estimator. We construct the following function

$$(\tilde{Y} - B\beta)'(\tilde{Y} - B\beta) + k\left((\beta + \hat{\beta}_{PE})'(\beta + \hat{\beta}_{PE}) - c\right) \tag{11}$$

To solve this function, we can get the new Profile-ridge-type estimator:

$$\hat{\beta}_{PRTE}(k) = (B'B + kI)^{-1}(B'\tilde{Y} - k\hat{\beta}_{PE}) \tag{12}$$

where $k > 0$ is the parameter, we call this new estimator as Profile-ridge-type estimator.

3. The properties of the new estimator

Now we will compare the new estimator with the Profile least squares estimator in the MSE criterion.

Theorem 3.1 (1) If $\Phi_i < 0$ and $\Omega_i > 0$, then for any k, we have $MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PE}\right]$.

(2) If $\Phi_i < 0$ and $\Omega_i > 0$, when $k > \max\limits_{1\le i\le p}\left(\frac{\Omega_i}{\Phi_i}\right)$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PE}\right]$.

(3) If $\Phi_i > 0$ and $\Omega_i > 0$, when $0 < k < \min\limits_{1\le i\le p}\left(\frac{\Omega_i}{\Phi_i}\right)$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PE}\right]$.

where $\Phi_i = \omega_i^2\delta_i^2 + o_{ii}$ and $\Omega_i = \omega_i(\sigma^2 l_{ii} + o_{ii} + \gamma_i^2)$, $i = 1, ..., p$.

Proof If $rank(X) = p$, then we have $rank(B) = p$. So we have $B'B$ is a positive definite matrix. Therefore we can get

$$B'B = Gdiag(\omega_1, ..., \omega_p)G' = G\Lambda G' \tag{13}$$

where $\omega_i > 0$, $i = 1, ..., p$.

By (12), we get that

$$\begin{aligned} E\left[\hat{\beta}_{PRTE}(k)\right] &= (B'B+kI)^{-1}(B'\tilde{Y} - k\hat{\beta}_{PE}) \\ &= (B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}B'(B\beta+\tilde{M}) \end{aligned} \tag{14}$$

and

$$\begin{aligned} Cov\left[\hat{\beta}_{PRTE}(k)\right] &= \sigma^2(B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}\tilde{X}'(I-U)(I-U)'B \\ &\quad \times(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1} \end{aligned} \tag{15}$$

Thus for equations (14) and (15), we obtain

$$\begin{aligned} & MSE\left[\hat{\beta}_{PRTE}(k)\right] \\ &= trCov\left[\hat{\beta}_{PRTE}(k)\right] + Bias'\left[\hat{\beta}_{PRTE}(k)\right]Bias\left[\hat{\beta}_{PRTE}(k)\right] \\ &= tr\{\sigma^2(B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}B'(I-U)(I-U)'B \\ &\quad \times(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1}\} \\ &\quad +tr\left[(B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}B'(B\beta+\tilde{M})-\beta\right] \\ &\quad \times\left[(B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}B'(B\beta+\tilde{M})-\beta\right]' \\ &\quad \times(B'B)^{-1}B'\tilde{M}\tilde{M}'B(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1}\} \\ &= tr(\sigma^2(B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}B'(I-U)(I-U)'B \\ &\quad \times(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1}) + tr((B'B+kI)^{-1}(B'B-kI)) \\ &\quad -4ktr\left[(B'B+kI)^{-1}\beta\tilde{M}'B(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1}\right] \\ &\quad +4k^2tr\left[(B'B+kI)^{-1}\beta\beta'(B'B+kI)^{-1}\right] \\ &= h_1+h_2+h_3+h_4 \end{aligned} \tag{16}$$

As we all know, for any matrix A and B, we have $tr(AB) = tr(BA)$. Then we have

$$\begin{aligned} h_1 &= tr\{\sigma^2(B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}B'(I-U)(I-U)'B \\ &\quad \times(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1}\} \\ &= \sum_{i=1}^{p}\frac{\sigma^2 l_{ii}(\omega_i-k)^2}{\omega_i^2(\omega_i+k)^2} \end{aligned} \tag{17}$$

where $L = G'B'(I-U)(I-U)'BG = (l_{ij})_{p\times p}$.

$$\begin{aligned} h_2 &= tr\{(B'B+kI)^{-1}(B'B-kI)(B'B)^{-1}B'\tilde{M}\tilde{M}'B \\ &\quad \times(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1}\} \end{aligned}$$

$$= \sum_{i=1}^{p} \frac{\gamma_i^2(\omega_i - k)^2}{\omega_i^2(\omega_i + k)^2} \tag{18}$$

where $\gamma = (\gamma_1, ..., \gamma_p) = \tilde{M}'BG$.

$$h_3 = -4ktr\left[(B'B+kI)^{-1}\beta\tilde{M}'B(B'B)^{-1}(B'B-kI)(B'B+kI)^{-1}\right]$$
$$= \sum_{i=1}^{p} \frac{-4k(\omega_i - k)o_{ii}}{\omega_i^2(\omega_i + k)^2} \tag{19}$$

where $O = G'\beta\tilde{M}'\tilde{X}G = (o_{ij})_{p\times p}$.

$$h_4 = 4k^2tr\left[(B'B+kI)^{-1}\beta\beta'(B'B+kI)^{-1}\right]$$
$$= \sum_{i=1}^{p} \frac{4k^2\delta_i^2}{(\omega_i + k)^2} \tag{20}$$

where $\delta = (\delta_1, ..., \delta_p)' = G'\beta$. Thus we have

$$MSE\left[\hat{\beta}_{PRTE}(k)\right] = \sum_{i=1}^{p} \frac{\sigma^2 l_{ii}(\omega_i - k)^2}{\omega_i^2(\omega_i + k)^2} + \sum_{i=1}^{p} \frac{\gamma_i^2(\omega_i - k)^2}{\omega_i^2(\omega_i + k)^2} + \sum_{i=1}^{p} \frac{-4k(\omega_i - k)o_{ii}}{\omega_i^2(\omega_i + k)^2} + \sum_{i=1}^{p} \frac{4k^2\delta_i^2}{(\omega_i + k)^2} \tag{21}$$

Setting $k = 0$, we obtain

$$MSE\left[\hat{\beta}_{PE}\right] = \sum_{i=1}^{p} \frac{\sigma^2 a_{ii}}{\omega_i^2} + \sum_{i=1}^{p} \frac{\omega_i^2}{\omega_i^2} \tag{22}$$

Thus by (21) and (22), we have

$$\nabla_1 = MSE\left[\hat{\beta}_{PRTE}(k)\right] - MSE\left[\hat{\beta}_{PE}\right]$$
$$= \sum_{i=1}^{p} \frac{\sigma^2 l_{ii}(\omega_i - k)^2}{\omega_i^2(\omega_i + k)^2} + \sum_{i=1}^{p} \frac{\gamma_i^2(\omega_i - k)^2}{\omega_i^2(\omega_i + k)^2} + \sum_{i=1}^{p} \frac{-4k(\omega_i - k)o_{ii}}{\omega_i^2(\omega_i + k)^2} + \sum_{i=1}^{p} \frac{4k^2\delta_i^2}{(\omega_i + k)^2} - \sum_{i=1}^{p} \frac{\sigma^2 a_{ii}}{\omega_i^2} + \sum_{i=1}^{p} \frac{\omega_i^2}{\omega_i^2}$$
$$= 4k\sum_{i=1}^{p} \frac{k(\omega_i^2\delta_i^2 + o_{ii}) - \omega_i(\sigma^2 l_{ii} + o_{ii} + \gamma_i^2)}{\omega_i^2(\omega_i + k)^2} \tag{23}$$

where $\Phi = \lambda_i^2\delta_i^2 + o_{ii}$ and $\Omega = \lambda_i(\sigma^2 l_{ii} + o_{ii} + \gamma_i^2)$, $i = 1, ..., p$. Then

(1) If $\Phi_i < 0$ and $\Omega_i > 0$, then for any k, we have $MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PE}\right]$.

(2) If $\Phi_i < 0$ and $\Omega_i > 0$, when $k > \underset{1\le i\le p}{max}\left(\frac{\Omega_i}{\Phi_i}\right)$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PE}\right]$.

(3) If $\Phi_i > 0$ and $\Omega_i > 0$, when $0 < k < \underset{1\le i\le p}{min}\left(\frac{\Omega_i}{\Phi_i}\right)$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PE}\right]$.

Now we will compare estimator (12) with the Profile-ridge estimator in the MSE criterion.

Theorem 3.2
(1) If $\Upsilon_i < 0$ and $\Psi_i > 0$, then for any k, we have $MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PRE}(k)\right]$.
(2) If $\Upsilon_i < 0$ and $\Psi_i > 0$, when $k > \max\limits_{1\le i\le p}\left(\frac{\Upsilon_i}{\Psi_i}\right)$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PRE}(k)\right]$.
(3) If $\Upsilon_i > 0$ and $\Psi_i > 0$, when $0 < k < \min\limits_{1\le i\le p}\frac{\Upsilon_i}{\Psi_i}$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PRE}(k)\right]$.
where $\Upsilon_i = \sigma^2 l_{ii} + 3\delta_i^2\omega_i^2 + 4o_{ii} + \gamma_i^2$ and $\Psi_i = \omega_i(2\sigma^2 l_{ii} + 4o_{ii} - 2o_{ii}\omega_i + 2\gamma_i^2)$, $i = 1,...,p$.

Proof By the same way given in theorem 3.1, we can get the MSE of the Profile-ridge estimator

$$MSE\left[\hat{\beta}_{PRE}(k)\right] = \sum_{i=1}^{p}\frac{\sigma^2 l_{ii}}{(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{\gamma_i^2}{(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{-2ko_{ii}}{(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{k^2\delta_i^2}{(\omega_i+k)^2} \quad (24)$$

Then by (21) and (24), we have

$$\begin{aligned}\nabla_2 &= MSE\left[\hat{\beta}_{PRTE}(k)\right] - MSE\left[\hat{\beta}_{PRE}(k)\right]\\ &= \sum_{i=1}^{p}\frac{\sigma^2 l_{ii}(\omega_i-k)^2}{\omega_i^2(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{\gamma_i^2(\omega_i-k)^2}{\omega_i^2(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{-4k(\omega_i-k)o_{ii}}{\omega_i^2(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{4k^2\delta_i^2}{(\omega_i+k)^2}\\ &\quad - \left[\sum_{i=1}^{p}\frac{\sigma^2 l_{ii}}{(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{\gamma_i^2}{(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{-2ko_{ii}}{(\omega_i+k)^2} + \sum_{i=1}^{p}\frac{k^2\delta_i^2}{(\omega_i+k)^2}\right]\\ &= \sum_{i=1}^{p}\frac{k(\sigma^2 l_{ii} + 3\delta_i^2\omega_i^2 + 4o_{ii} + \gamma_i^2) - \omega_i(2\sigma^2 l_{ii} + 4o_{ii} - 2o_{ii}\omega_i + 2\gamma_i^2)}{\omega_i^2(\omega_i+k)^2} \end{aligned} \quad (25)$$

where $\Upsilon_i = \sigma^2 l_{ii} + 3\delta_i^2\omega_i^2 + 4o_{ii} + \gamma_i^2$ and $\Psi_i = \omega_i(2\sigma^2 l_{ii} + 4o_{ii} - 2o_{ii}\omega_i + 2\gamma_i^2$, $i = 1,...,p$. Then by (25), we can get
(1) If $\Upsilon_i < 0$ and $\Psi_i > 0$, then for any k, we have $MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PRE}(k)\right]$.
(2) If $\Upsilon_i < 0$ and $\Psi_i > 0$, when $k > \max\limits_{1\le i\le p}\left(\frac{\Upsilon_i}{\Psi_i}\right)$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PRE}(k)\right]$.
(3) If $\Upsilon_i > 0$ and $\Psi_i > 0$, when $0 < k < \min\limits_{1\le i\le p}\frac{\Upsilon_i}{\Psi_i}$,$MSE\left[\hat{\beta}_{PRTE}(k)\right] < MSE\left[\hat{\beta}_{PRE}(k)\right]$.

4. Monte Carlo Simulation Experiments

In this section we will present a Monte Carlo simulation to further illustrate the theoretical results.

Consider this model:

$$Y_i = X_i'\beta + Z_i'\alpha(T_i) + e_i, i = 1,...,n \quad (26)$$

The data generation of X_{ij} adopts the same method as Kibria [13], which is given by:

$$X_{ij} = \left(1-\rho^2\right)^{1/2}\theta_{ij} + \rho\theta_{ip}, i = 1,2,\ldots,n, j = 1,2,\ldots,p$$

where θ_{ij} is the random number generated by the standard normal random variable, ρ is the given constant. In this article, we consider three cases $\rho = 0.95, 0.99, 0.999$, set $p = 4, n = 100$, $Z_i \sim N(2,1)$, $T_i \sim U(0,1)$, $\beta = (1,2,2.5,1.5)'$, $\alpha(T_i) = 4 + 3cos(2\pi T_i)$ and (1) $e_i \sim N(0,1)$, (2) $e_i \sim U(0,1)$.We choose the kernel function $N_h(.) = \frac{-(.)^2/2h^2}{\sqrt{2\pi}h}$ and $h = sd(T_i)n^{-1/5}$.

The simulated mean squared error (MSE) is used to compare the estimators, which can be calculated as follows:

$$MSE\left(\hat{\beta}_{ji}\right) = \frac{1}{1000}\sum_{i=1}^{1000}\sum_{j=1}^{4}(\hat{\beta}_{ji} - \beta_j)^2$$

where $\hat{\beta}_{ji}$ is any estimator considered in this paper in the i^h repetition. Tables 1-6 show the calculation results.

Table 1 Estimated MSE when $\rho = 0.95$ and $e_i \sim N(0,1)$

	$k=0.01$	$k=0.03$	$k=0.05$	$k=0.07$	$k=0.1$	$k=0.3$
$\hat{\beta}_{PE}$	0.3578	0.3534	0.3507	0.3574	0.3582	0.3506
$\hat{\beta}_{PRE}(k)$	0.3370	0.3412	0.3563	0.3320	0.3307	0.3132
$\hat{\beta}_{PRTE}(k)$	0.3362	0.3391	0.3521	0.3270	0.3243	0.3045

Table 2 Estimated MSE when $\rho = 0.99$ and $e_i \sim N(0,1)$

	$k=0.01$	$k=0.03$	$k=0.05$	$k=0.07$	$k=0.1$	$k=0.3$
$\hat{\beta}_{PE}$	1.7300	1.7377	1.7326	1.7334	1.7434	1.7365
$\hat{\beta}_{PRE}(k)$	1.7098	1.6303	1.6705	1.4434	1.5140	1.2817
$\hat{\beta}_{PRTE}(k)$	1.6900	1.5760	1.5865	1.3393	1.3757	1.1130

Table 3 Estimated MSE when $\rho = 0.999$ and $e_i \sim N(0,1)$

	$k=0.01$	$k=0.03$	$k=0.05$	$k=0.07$	$k=0.1$	$k=0.3$
$\hat{\beta}_{PE}$	17.1246	17.6108	17.7194	16.8768	17.2419	17.2334
$\hat{\beta}_{PRE}(k)$	15.2621	12.1293	9.6118	8.8970	6.9141	6.6659
$\hat{\beta}_{PRTE}(k)$	13.5342	8.5520	5.4902	4.3146	3.0333	3.6161

Table 4 Estimated MSE when $\rho = 0.95$ and $e_i \sim U(0,1)$

	$k=0.01$	$k=0.03$	$k=0.05$	$k=0.07$	$k=0.1$	$k=0.3$
$\hat{\beta}_{PE}$	0.1267	0.1295	0.1260	0.1287	0.1279	0.1275
$\hat{\beta}_{PRE}(k)$	0.1224	0.1090	0.1147	0.1167	0.1063	0.1137
$\hat{\beta}_{PRTE}(k)$	0.1222	0.1085	0.1136	0.1152	0.1056	0.1184

Table 5 Estimated MSE when $\rho = 0.99$ and $e_i \sim U(0,1)$

	$k=0.01$	$k=0.03$	$k=0.05$	$k=0.07$	$k=0.1$	$k=0.3$
$\hat{\beta}_{PE}$	0.5620	0.5687	0.5617	0.5628	0.5689	0.5737
$\hat{\beta}_{PRE}(k)$	0.5361	0.5505	0.5611	0.5225	0.5093	0.4830
$\hat{\beta}_{PRTE}(k)$	5305	0.5346	0.5389	0.4945	0.4844	0.5679

Table 6 Estimated MSE when $\rho = 0.999$ and $e_i \sim U(0,1)$

	$k=0.01$	$k=0.03$	$k=0.05$	$k=0.07$	$k=0.1$	$k=0.3$
$\hat{\beta}_{PE}$	5.5115	5.5864	5.5720	5.5325	5.5903	5.4848
$\hat{\beta}_{PRE}(k)$	4.9358	3.9946	3.5626	3.1463	2.7525	5.0712
$\hat{\beta}_{PRTE}(k)$	4.4145	2.9933	2.4478	2.1850	2.3009	5.1823

Based on Tables 1-6, we can drawn the following results:
(1) With the increase of ρ, MSE of all estimates increases .
(2) $MSE(\hat{\beta}_{PRTE}(k)) < MSE(\hat{\beta}_{PE})$.
(3) In most cases, $\hat{\beta}_{PRTE}(k)$ has smaller MSE than the $\hat{\beta}_{PRE}(k)$.

5. Conclusions

This paper proposes a new profile ridge estimator to address multicollinearity in partially linear varying-coefficient models. The necessary and sufficient conditions are provided under which the profile ridge estimator outperforms the profile least squares estimator and the profile ridge estimator in terms of mean squared error. The theoretical results are verified through simulation analysis.

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Mask Recognition Method Based on Improved YOLOV5 Model

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Abstract. Target detection technology based on deep learning is a hot research topic today. Since the covid-19, wearing a mask when going out has become one of the necessary and effective means of protection. In order to realize automatic real-time recognition of face mask wearing, this paper proposes a mask recognition method based on an improved YOLOv5 architecture. By adding the CA attention mechanism module, the feature extraction ability of the overall network is enhanced, and problems such as missed detections and occlusions are mitigated. The α-EIoU loss function is introduced to replace the GIOU loss function, which can obtain higher-quality localized image regions faster and more accurately, generate bounding boxes and predict categories. The detection speed of the model is improved by changing the mode speed of the backbone network CSPBlock. The experimental results show that based on the improved Yolov5 target detection algorithm, the accuracy rate of mask recognition can reach 95.7%, which is 1.2% higher than that of Yolov5. The GUI is designed to be directly deployed to the PC to meet the real-time mask recognition requirements.

Keywords. YOLOV5, Mask Recognition, Attention Mechanism

1. Introduction

With the emergence of the COVID-19 pandemic, wearing masks has become an essential protective measure when going outside due to the virus's high transmissibility and rapid spread. Additionally, the risks of "environmental transmission" and virus mutations emphasize the importance of consistently wearing masks to curb the spread of the virus [1]. However, manually monitoring mask usage in public places is both inefficient and impractical, especially in crowded areas like train stations and airports. Therefore, automatic, real-time mask detection systems offer a more effective solution for ensuring compliance with mask-wearing guidelines during the pandemic.

In recent years, advancements in target detection techniques, which combine computer vision and image processing, have made them applicable to a wide range of scenarios, such as detecting cars, pedestrians, and gestures. These technologies, compared to traditional detection methods, have been widely used in video surveillance, autonomous driving, traffic monitoring, UAV scene analysis, and robotic vision [2]. Convolutional neural networks (CNNs), a key component in these developments, have spurred progress in deep learning-based object detection, offering enhanced potential for

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computer vision applications. Object detection algorithms based on deep learning are generally categorized into single-stage and two-stage models [3].

Traditional object detection techniques laid the foundation for learning features from samples, as proposed by Papageorgiou et al [4]. Lowe et al introduced motion target detection using SIFT invariant features [5], while Viola et al pioneered robust, real-time detection using a cascade classifier [6]. Additional techniques include optical flow, frame differencing, and background subtraction [7], with classifiers such as Bagging [8], AdaBoost [9], and Support Vector Machine (SVM) [10] playing crucial roles.

In deep learning, object detection algorithms are divided into two processes: recognition and classification, which are used to determine the location and category of the target. Two-stage methods, represented by models like Faster RCNN, first generate candidate frames and then detect and recognize them. These methods extract information from candidate frames before using CNNs for detection. Notable two-stage models include SPPNet [11], Fast RCNN [12], Faster RCNN [13], and R-FCN [14]. On the other hand, single-stage methods, such as YOLO and SSD, streamline the process by performing feature extraction and regression simultaneously, offering a simpler structure and computational efficiency. Key single-stage models include YOLO [15], SSD [16], DSSD [17], and CornerNet [18].

SNELM (SqueezeNet-guided ELM) is a deep learning model that merges features from SqueezeNet with the Extreme Learning Machine (ELM) for COVID-19 detection [19]. SqueezeNet, a lightweight CNN, has fewer parameters compared to other CNN architectures, while ELM offers faster training speeds and better generalization. In SNELM, SqueezeNet functions as the feature extractor, and the extracted features are classified by ELM. Experiments show that SNELM achieves high accuracy and outperforms other models for COVID-19 detection. Additionally, the RAVGF (rotation angle vector grid-based fractional Fourier entropy) method, used for recognizing secondary pulmonary tuberculosis, captures the texture and structural details of lung images through entropy calculations of fractional Fourier transform coefficients. While these two methods employ different techniques, they share the goal of identifying diseases from medical images. Zhao et al. proposed DiGAN, a GAN-based framework for addressing data imbalance in medical datasets, which has inspired similar applications in vision tasks such as mask detection [20]. CENN, a capsule-enhanced neural network originally developed for robust speech emotion recognition [21], demonstrates the potential of capsule-based architectures in improving feature extraction and classification robustness.

Various single-stage and two-stage object detection networks have been applied to detecting whether individuals are wearing face masks. However, these models face challenges in crowded environments, where occlusion, diverse mask styles, and colors complicate detection. YOLOv5, known for its simplicity and high performance in real-time detection tasks, was selected for this study's mask recognition task. Several improvements were made to YOLOv5 to enhance its effectiveness in mask detection. Xu et al. proposed a lightweight mask detection model based on YOLOv5, incorporating ShuffleCANet as the backbone network and introducing BiFPN for feature fusion [22]. They replaced the traditional loss function with α-CIoU, and achieved an mAP of 95.2% on the AIZOO dataset, improving by 4.4% compared to the original YOLOv5.Wang et al. proposed a mask detection method based on the YOLO-GBC network [23], which integrates a Global Attention Mechanism (GAM), cross-layer feature fusion, and Content-Aware ReAssembly of FEatures (CARAFE), and replaces traditional NMS with Soft-NMS to improve detection accuracy and recall. Their model achieved a mAP of

91.2% and a detection speed of 64 FPS on the mask detection dataset. TGBFormer combines a spatial-temporal Transformer and a GraphFormer with a global-local feature blender to enhance video object detection, achieving 86.5% mAP on ImageNet VID [24].

This paper implements a YOLOv5-based single-stage detection algorithm to identify whether individuals are wearing face masks. The model's accuracy is boosted by modifying the backbone's CSP module, integrating a CA attention mechanism, and incorporating the α-EIoU loss function. These modifications address issues of low resolution and suboptimal recognition in challenging conditions such as background clutter and occlusion, ultimately improving the performance of face mask detection. Our work builds on YOLOv5, focusing on lightweight improvements for real-time face mask detection. Unlike YOLOv5x6, YOLOv7, and YOLOv8, which enhance model depth, width, or use NAS for general detection, we target occlusion handling and reduction of missed detections. Instead of using heavier hybrid attention modules (e.g., SE, CBAM, self-attention), we introduce Coordinate Attention (CA), which efficiently encodes positional information with low computational cost, enhancing feature extraction under occlusions. We replace traditional loss functions (GIoU, DIoU, CIoU) with α-EIoU, improving bounding box localization and accelerating convergence by explicitly optimizing width, height, and center distance. Rather than redesigning the backbone (as in YOLOv8's RepConv), we optimize CSPBlock to boost inference speed while preserving strong feature extraction, balancing accuracy and efficiency. Our method is specifically tailored for mask recognition, featuring a GUI-based PC deployment system to meet real-time monitoring requirements in practical environments.

2. YOLOv5 fundamentals

YOLO is a classical one-stage detection algorithm that treats object detection as a regression task, balancing real-time performance and accuracy through multi-scale prediction. YOLOv3 improved detection accuracy by introducing Feature Pyramid Networks (FPN) and an anchor mechanism. YOLOv4 further optimized the network structure and training techniques, integrating CSPDarknet53, Mish activation, and FPN+PAN architecture. It also employed advanced methods like Mosaic augmentation, CIOU_Loss, and DIOU_nms to enhance training and prediction performance. Figure 1 illustrates the YOLOv4 network structure.

The CSPDarknet53 backbone is derived from Darknet53, with CSPNet (Cross Stage Partial Network) added to its five large residual blocks. This CSPNet module enhances the learning capacity of the CNN, eliminating computational bottlenecks and reducing memory usage, ultimately improving both inference speed and accuracy by reducing the network's computational load.

FPN (Feature Pyramid Network) is used to improve detection speed and accuracy, particularly for small objects, by merging features extracted from different scales. This network extracts and fuses deep and shallow features across three different scales, improving the detection of small targets. YOLOv4's FPN incorporates three output layers of varying sizes, corresponding to large, medium, and small targets. The smaller-scale output maps are upsampled and fused with the deeper layers, allowing deep features to merge with shallow ones, thus retaining more detailed information and improving accuracy. The addition of the PAN structure further enhances both localization and semantic features in the network. Figure 2 depicts the FPN+PAN structure.

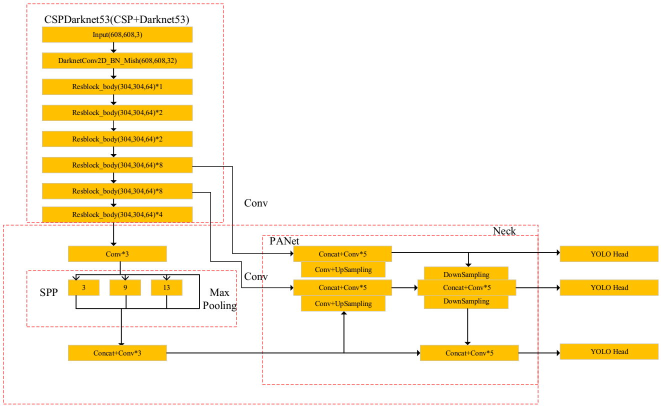

Figure 1. YOLOv4 network structure diagram [25]

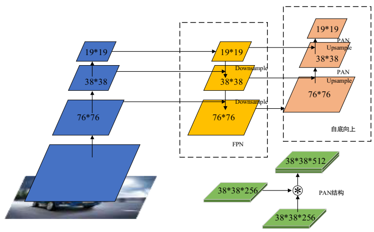

Figure 2. FPN+PAN structure diagram

YOLOv5 builds upon the foundation laid by YOLOv4 and offers multiple various object detector models, including YOLOv5x, YOLOv5s, YOLOv5l, and YOLOv5m, which are available in the public domain. Its key advantage is its rapid detection capability, achieving an inference speed of 140 FPS, which makes it ideal for real-time applications on both mobile devices and PCs. Among these variants, YOLOv5s is the most compact, having the smallest depth and feature map width [22]. The other versions increase in complexity by expanding the depth and width of the network. The architecture and training techniques have also undergone further improvements.

As depicted in Figure 3, the YOLOv5s architecture is structured around four key elements: Input, Backbone, Neck, and Prediction. The Input component features mosaic augmentation, adaptive anchor generation, and automatic image scaling. Focus and CSP modules are integrated into the Backbone, with CSP modules structured differently across the Backbone and Neck sections. In the Neck, an FPN+PAN combination is employed, while the prediction layer utilizes the GIOU_Loss function for more accurate bounding box regression [26].

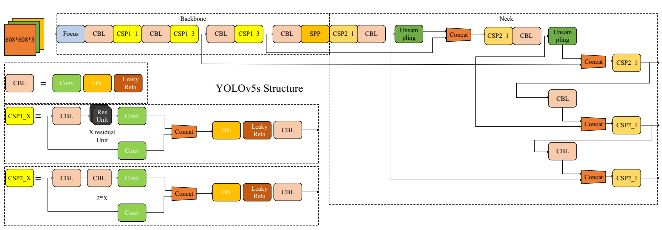

Figure 3. YOLOV5s network structure diagram

The Focus structure in YOLOv5s slices the input image into four parts, expanding the channel dimension from 3 to 12 without losing information. This sliced and stitched image undergoes convolution, producing a two-fold feature map while preserving key features. It effectively transforms a 640×640×3 input into a 320×320×32 feature map after one convolution. This design enhances feature extraction by reducing resolution while maintaining essential information. Figure 4 illustrates the slicing process and provides a module diagram of the Focus structure.

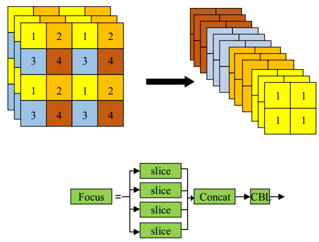

Figure 4. The principle of the Focus structure for slicing operation and the schematic diagram of the Focus module

3. Improved YOLOv5 algorithm

3.1. CSP module network structure

Darknet53 is a backbone feature extraction network introduced in YOLOv4 algorithm based on YOLOv3 backbone network Darknet53, which borrows the CSPNet algorithm. Among them, the structure of the Darknet53 network is shown in Figure 5 DarkNet-53 network introduces residual structure (Residual) and full convolution method, which greatly reduces network training difficulty. The entire backbone of DarkNet-53 contains 53 Convolutional Layers with 1*1 and 3*3 size convolutional kernels.

Number	Filter	Size/Stride	Number of filters	Output
	Conv	3*3/1	32	416*416
	Conv	2*2/2	64	208*208
1x	Conv	1*1/1	32	
	Conv	1*1/1	64	
	Residual			208*208
	Conv	3*3/2	128	104*104
2x	Conv	3*3/2	64	
	Conv	3*3/2	128	
	Residual			104*104
	Conv	3*3/2	256	52*52
8x	Conv	3*3/2	128	
	Conv	3*3/2	256	
	Residual			52*52
	Conv	3*3/2	512	26*26
8x	Conv	3*3/2	256	
	Conv	3*3/1	512	
	Residual			26*26
	Conv	3*3/2	1024	13*13
4x	Conv	1*1/1	512	
	Conv	3*3/1	1024	
	Residual			13*13
	Average pooling		Global	
	Full Connected		1000	
	Softmax			

Figure 5. DarkNet-53 network structure diagram

In DarkNet-53, the DBL unit constructs convolutional layers using convolution, batch normalization, and Leaky ReLU, eliminating fully connected and max pooling layers. The Residual module, based on ResNet, integrates 1×1 and 3×3 convolutions with shortcut connections to enhance network depth while alleviating gradient vanishing and overfitting [26], as illustrated in Figure 5.

To address issues like gradient vanishing and overfitting that can arise from overly deep networks, the Residual module is employed. This approach is inspired by the residual architecture of ResNet and utilizes both 1x1 and 3x3 convolutional kernels to combine features from different layers. It incorporates a shortcut connection technique, where the output from the current layer and the preceding convolutional layer are summed together to form the input for the next convolutional layer. Figure 6 illustrates the structure of the residual block.

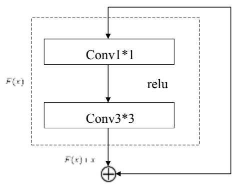

Figure 6. Residual block structure diagram

The CSP (Cross Stage Partial) module consists of two base layers connected through a cross-stage hierarchy. This design offers significant advantages, such as reduced computational load, enhanced detection speed, improved learning capability of the CNN, and alleviation of computational bottlenecks and memory usage in the network model. Figure 7 illustrates the structure of the CSP module.

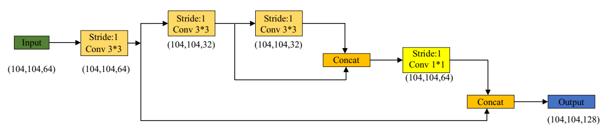

Figure 7. CSP module structure diagram

The CSPNet (Cross Stage Partial Network) module reduces the computational and memory burden of CNNs by partitioning feature maps: one part undergoes convolution while the other is passed directly, and the two are later merged. It also introduces Cross Stage Connections to enhance feature reuse and network learning capability.YOLOv5 adopts two CSP structures: CSP1_X and CSP2_X. CSP1_X, used in the backbone, integrates residual blocks to improve gradient flow and extract fine-grained features, preventing degradation in deeper networks.CSP2_X, used in the neck, replaces ResUnits with dual CBL modules, splitting features into two paths for stronger fusion. Moreover, YOLOv5 improves CSP1_X by embedding residual structures more effectively, further refining feature extraction. Figures 8 and 9 show the CSP1_X, CSP2_X, and the improved CSP1_X structures.

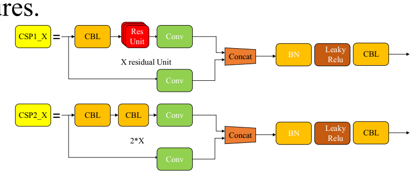

Figure 8. CSP1_X structure and CSP2_X structure [26]

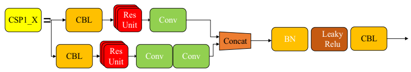

Figure 9. Improve CSP1_X structure [26]

3.2. Introduction of CA attention mechanism

To accelerate target detection, the Coordinate Attention (CA) module is incorporated into the YOLOv5 framework. Unlike the traditional channel attention mechanism, the CA module transforms the feature tensor into a single feature vector via 2D global pooling. The CA mechanism consists of two stages: encoding one-dimensional features in two spatial directions and then aggregating them. This approach enables capturing long-range dependencies in one direction, while retaining exact position information along the other.

The obtained feature maps are transformed through encoding into direction-sensitive and position-sensitive maps, which complement the input feature maps, enhancing the representation of the target objects. Figure 10 Demonstrates the structure of the CA module.

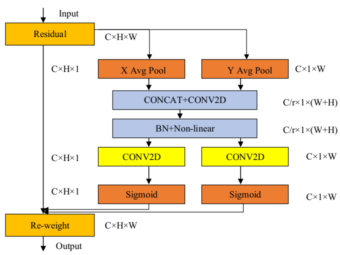

Figure 10. CA attention mechanism module network structure [27]

The CA mechanism enhances feature representation by recalibrating channel-wise features. The backbone is enhanced by embedding the CA module architecture of YOLOv5.The CA module is typically inserted after specific convolutional layers or residual blocks in the backbone. During forward pass, input features are passed through the CA module to obtain enhanced features. Define the CA Attention module comprising Global Average Pooling, Fully Connected, and Sigmoid layers. Modify the YOLOv5 backbone to include CAAttention after specific layers. During forward pass, apply the CAAttention module to feature maps obtained from the backbone. Figure 11 shows how the use of the CA attention mechanism is integrated into the YOLOv5 architecture.

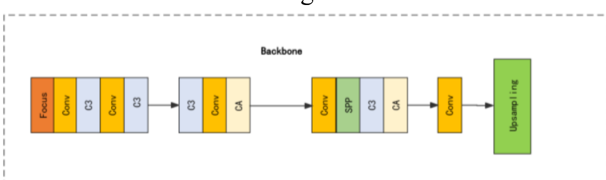

Figure 11. CA attention mechanism module network structure integrated into the YOLOv5

The design of the Coordinate Attention (CA) mechanism provides is an advanced module designed to enhance the feature representation in convolutional neural networks (CNNs). Unlike traditional attention mechanisms that focus separately on spatial or channel-wise features, CA integrates both, enabling the network to capture richer contextual information and finer details. The CA mechanism divides the attention process into two stages: applying coordinate attention along the height and width dimensions. This design permits the network to model distant relationships in one direction without losing precise positional details in the perpendicular direction. By splitting the attention process, the CA mechanism balances computational efficiency with improved feature extraction, ensuring the network can focus on both spatial locations and channel dependencies. This leads to enhanced performance in tasks like object detection and image recognition. The process includes splitting the input feature map into two branches to process height and width independently, applying global average pooling to capture global context, generating attention maps for each dimension, and combining them to form the final attention map. The original feature map is then recalibrated using this attention map, refining the feature representations.

By integrating the CA mechanism into the YOLOv5 network, the model becomes more effective at extracting relevant features, improving its performance in tasks requiring detailed feature recognition. This addition reduces missed detections and increases robustness against occlusions and variations in object appearances. The CA module is also versatile and can be easily incorporated into other CNN architectures, making it a valuable enhancement for models like YOLOv5.

3.3. Loss function

In machine learning, the loss function is essential for guiding model training by measuring the difference between the model's predictions and actual target values. The objective is to minimize this loss to improve model accuracy and performance. In object detection, the loss function must handle two tasks: object localization within an image and classification into predefined categories. Therefore, object detection loss functions combine these components. Commonly used loss functions include classification loss, which measures how well the model predicts class labels (e.g., Cross-Entropy Loss and Focal Loss), and localization loss, which assesses the accuracy of predicted bounding boxes (e.g., L1, L2 Losses, and IoU-based losses like GIoU and DIoU).

In the YOLOv5s model, gradient descent is applied using a loss function aiming to lessen the discrepancy between the prediction and ground truth bounding boxes. The network's weights and biases are updated iteratively, refining the coordinate offsets and category scores of each anchor box to achieve the lowest loss. The total loss is comprised of confidence loss, classification loss, and bounding box loss, with binary cross-entropy loss function utilized for confidence prediction and class assignment, as shown in Equation (1). The α-EIoU loss function is used to improve bounding box localization.

$$BCELoss = \begin{cases} -\log P', y = 1 \\ -\log(1 - P'), y = 0 \end{cases} \tag{1}$$

where BCELoss denotes the BCE loss function, P' represents the sample predicted value, and y represents the sample really category.

Based on the IOU, the CIOU version is proposed by taking the overlap region, centroid distance and aspect ratio into account. A better convergence effect is obtained and the bounding box regression is performed more efficiently. the CloU loss function is shown in Eq. (2).

$$CIOULoss = 1 - IOU + \left| \frac{\rho^2(b, b^{gt})}{c^2} \right| + \beta\upsilon \tag{2}$$

The CIOU loss function enhances detection speed by proportional relationship of width and height between the prediction and ground truth (GT) frames. However, it still encounters certain limitations. For instance, when the predicted frame regresses and its aspect ratio aligns linearly with the GT frame, the CIOU's penalty factor becomes ineffective. Additionally, based on the gradient formula for the width and height of the prediction frame, an increase in one dimension (either width or height) necessitates a decrease in the other, preventing simultaneous growth in both dimensions. To address these issues, the EIOU loss function was incorporated. It resolves the limitations of CIOU by refining the penalty mechanism. The EIOU loss function is defined in Eq. (3).

$$\begin{aligned} &L_{EIOU} = L_{IOU} + L_{\text{dis}} + L_{asp} = \\ &1 - IOU + \frac{\rho^2(b, b^{gt})}{c^2} + \frac{\rho^2(w, w^{gt})}{c_w^{\ 2}} + \frac{\rho^2(h, h^{gt})}{c_h^{\ 2}} \end{aligned} \tag{3}$$

where Cw2 and Ch2 represent the minimal dimensions in width and height outside rectangle of the prediction frame and GT frame. And the loss function of EIOU consists of three parts: the overlap loss function of the prediction frame and the real frame, the central distance loss function, and the width and height loss functions. Thus, it makes the convergence speed faster.

In this paper, the use of the IOU loss function, which is scale-invariant for bounding boxes, allows for the development of a more efficient network model, and this way the loss function of all IOUs is uniformly added with a power value α, so that all loss functions become Eqs. (4).

$$\begin{aligned} &L_{\alpha-IOU} = 1 - IOU^{\alpha} \\ &L_{\alpha-GIOU} = 1 - IOU^{\alpha} + \left(\frac{\left|C - (B \cup B^{gt}\right|}{|C|}\right)^{\alpha} \\ &L_{\alpha-DIOU} = 1 - IOU^{\alpha} + \frac{\rho^{2\alpha}(b, b^{gt})}{c^{2\alpha}} \\ &L_{\alpha-CIOU} = 1 - IOU^{\alpha} + \frac{\rho^{2\alpha}(b, b^{gt})}{c^{2\alpha}} + (\beta v)^{\alpha} \\ &L_{\alpha-EIOU} = 1 - IOU^{\alpha} + \frac{\rho^{2\alpha}(b, b^{gt})}{c^{2\alpha}} + \frac{\rho^{2\alpha}(w, w^{gt})}{c_w^{\ 2\alpha}} + \frac{\rho^{2\alpha}(h, h^{gt})}{c_h^{\ 2\alpha}} \end{aligned} \tag{4}$$

The above are the overall modifications to enhance the detection performance of the overall network model by changing the structure of the CSP module in the backbone network as well as introducing the CA attention mechanism and the α-EIoU loss function. Figure 12 shows the structure of the improved YOLOv5s network model.

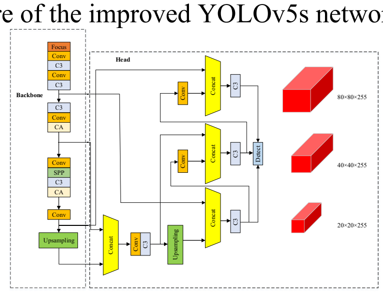

Figure 12. Improved YOLOv5s network model structure

4. Experiments and results

4.1. Setup and data used for experimentation

The environment used in the paper is: Anaconda environment with Keras version 2.24, PyTorch 1.7.1, CUDA 9.2 and the graphics card is NVDIA GTX2080.

The experimental dataset MaskData, used in this paper, is a collocation synthesis of multiple open source datasets from the web. A total of is included in the experimental dataset MaskData is 5300 images of human faces with and without masks. The dataset is a collection of face mask images collected across multiple backgrounds and lighting scenarios. Among them, the dataset contains images of face masks in various scenarios, such as with and without masks under various expressions that may occur in multiple people's communication in various scenarios such as offices and meetings. And the dataset MaskData is manually annotated using LabelImage. Figure 13 shows some of the data of the face Masks under different conditions in the dataset. In this paper, the dataset is divided into three parts: training set, validation set, and test set for the training of the model, which are divided by 80% designated for training, 10% for testing, and 10% for validation. After the training is completed, the model is fed back using the validation set, and the final model with the best results is obtained by changing the superparameter and then training again.

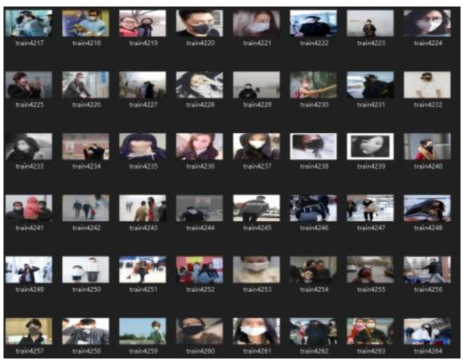

Figure 13. Partial data of face masks

4.2. Training strategy and result interpretation

The same dataset and identical training parameters were used across all experiments to ensure the consistency and reliability of the results. A strategy for learning rate decay using a polynomial function is used, setting the initial learning rate to 0.001, the batch size to 128, the smallest set of data per batch to 32, the momentum to 0.9, and the decay coefficient to 0.005. The learning rate is adjusted to 0.0001 after 100 batches.

4.2.1 Test set evaluation model

After the model training is completed, testing is completed in the test set. Model Precision (Precision), Model Recall (Recall) and Mean Average Precision (mAP) were used as the model's final assessment metrics, and the obtained results are shown in Table 1.

Table 1. YOLOv5 model comparison experiment results % [25]

Model	Precision	Recall
YOLOv3-tiny	78.70	89.90
SSD-Mobilenetv2	83.20	91.06
YOLOv5	92.82	90.77
YOLOv5 + CA	93.00	90.70
YOLOv5 + α-EIoU	92.95	91.00
YOLOv5 + improved CSP	93.10	90.85
(CA+improvedCSP)YOLOv5	93.57	90.56
(CA+α-EIoU+improvedCSP) YOLOv5	93.58	90.86

In this paper ablation experiments are compared to several other common target assays. As can be seen from the table, the optimized YOLOv5 architecture improves the network model detection accuracy and average accuracy to some extent due to the use of the improved CSP submodule in the backbone architecture and the introduction of the attention mechanism as well as the loss function. The introduction of the Coordinate Attention (CA) module alone enhances the mAP from 94.45% to 94.60%, indicating improved feature extraction and spatial information encoding. The replacement of the original GIoU loss with the α-EIoU loss function further elevates the mAP to 94.80%, reflecting more accurate localization and faster convergence during training. Incorporating the improved CSP structure individually increases the mAP to 94.65%, primarily by enhancing feature reuse and improving inference efficiency. The combination of CA and improved CSP results in mAP of 94.70%, illustrating their synergistic effect. Ultimately, the integration of CA, improved CSP, and α-EIoU achieves the highest mAP of 95.20%, demonstrating the complementary and cumulative impact of these enhancements on the overall detection performance.

4.2.2 Visualization showcasing detection performance

The detection effect is visualized on the NVDIA GTX2080 graphics card, which is shown in Figure 14.

Figure 14. Visualization showcasing detection outcomes

5. Conclusions

Automatic mask recognition in epidemic environments is a computer vision task. Existing face mask recognition methods often struggle with challenges like low resolution, background clutter, and occlusion. To address these issues and enhance mask recognition speed and accuracy, an advancement of the YOLOv5 algorithm is proposed in this paper. The algorithm optimizes detection speed by modifying the parallel residual architecture of the CSP1_X module within the backbone network. Additionally, it incorporates the CA attention mechanism and replaces replacing GIoU loss with α-EIoU loss for optimization for more accurate feature extraction and faster detection. Experimental results and visualizations demonstrate that the improved network performs well in various complex environments, showing notable improvements in detection accuracy and precision.

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Research on the Safety and Operational Status Intelligent Perception Technology of Mobile Machinery in General Bulk Cargo Terminals

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Abstract: Against the backdrop of the widespread use of information technology and intelligent methods to enhance operational safety in the port industry, issues such as the low level of automation in general bulk cargo terminal operations, insufficient operational status perception capabilities, and the lack of intelligent systems for operational assistance have become increasingly prominent. This paper focuses on mobile machinery at the terminal, analyzing its safety issues and accident causes in depth from four aspects: human factors, equipment and facilities, environment, and management. Intelligent perception technology for the operational status of mobile machinery was investigated, and an intelligent perception terminal for such machinery was proposed. The intelligent perception terminal enables individual vehicle to perceive humans, objects, and the environment intelligently, providing support for the safety assurance of multi-vehicle coordination at the terminal.

Keywords: General bulk Cargo terminal; Mobile Machinery; Safety;Intelligent Perception

1. Introduction

As China's economic ties with the rest of the world continue to deepen, ports, as critical transportation hubs, play a vital role in the country's economic development. Economic development has led to increasing demands for port operational efficiency and safety, while the information technology and intelligence level in Chinese ports has been rapidly advancing. However, due to constraints in operational process standardization, types of cargo, and other forms of transportation, issues such as low automation levels in general bulk cargo terminal operations, inadequate operational status perception, and the lack of intelligent systems for operational assistance have become increasingly prominent [1]. This issue is particularly severe in the complex operational areas involving mobile machinery, terminal personnel, cargo, and other equipment at general

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bulk cargo terminals, where these problems have significantly impacted operational safety and efficiency.

To address issues such as inadequate safety assurance capabilities for port facilities and equipment, and insufficient intelligent perception and system capabilities, the "Outline for Building a Strong Transportation Nation," issued by the State Council in September 2019, called for "strengthening the maintenance of transportation infrastructure, enhancing infrastructure operation monitoring, improving the specialization and informatization of maintenance, and enhancing the durability and reliability of facilities." In November 2019, the Ministry of Transport and nine other departments issued the "Guiding Opinions on Building World-Class Ports," which also emphasized "accelerating the construction of safe ports," "strengthening intrinsic safety," "gradually automating and unmanning high-risk operational areas and links," and "realizing real-time monitoring, intelligent perception, and risk warning for critical facilities and equipment."

2. Safety Issues of Mobile Machinery Operations

According to incomplete statistics, Chinese ports have over 20,000 production berths, of which 596 are dedicated to general bulk cargo terminals with a capacity of 10,000 tons or more. The scale of Chinese general bulk cargo terminals is continuously expanding, supported by the widespread use of various types of mobile machinery, which forms a critical foundation for efficient terminal operations [2]. However, with the increasing technological sophistication and complexity of cargo handling, storage, and transportation processes, the rising throughput and variety of hazardous goods, and the current situation of low terminal automation and human-machine interaction at the site, safety accidents at general bulk cargo terminals have become frequent, posing significant challenges to safe operations and management at these terminals.

The production operations at general bulk cargo terminals are characterized by multidimensional interactivity, process complexity, and a high frequency of safety incidents. These operations carry significant risks and have a relatively high accident rate. Unsafe behaviors are the primary root cause of accidents and represent a major stumbling block to both production safety and economic efficiency [3-4]. The existence of unsafe behaviors is primarily influenced by factors related to human factors, equipment and facilities, environment, and management, as shown in Table 1.

Table 1. Factors Contributing to Safety Accidents in General Bulk Cargo Terminal Operations

Main Factor	Sub-Factor	Main Factor	Sub-Factor
Human Factors	Incorrect positioning	Equipment Factors	Unstable cargo
	Violation of operating rules		Cargo roll-off
	Inadequate operational experience		Human-machine cross operations
	Distraction		Insufficient safety distance for machinery
	Fatigue		Vehicle collision
	Lack of safety awareness		Overloading
	Inadequate safety checks		Cargo collapse
	Improper emergency operation		Emergency braking
	Illegal command		Excessive speed
Environmental Factors	Chaotic working environment	Management Factors	Inadequate safety monitoring
	Obstructed vision		Insufficient safety supervision

	Scratching by lifting objects		Inadequate safety education
	Inadequate protective measures		Defective tools
	Lack of warning signs		Inadequate safety training

The factors contributing to safety accidents show that human factors, as well as accidents caused by mobile machinery such as collisions, falls, slips, cargo collapse, tipping, and dropped cargo injuries, account for a large proportion of the causes. This reflects the frequent interaction between people and machinery in the operational areas of general bulk cargo terminals, where workers and a large volume of cargo and handling equipment circulate in specific times, locations, and spaces. These interactions result in significant influences of human factors and mobile machinery on the safety of terminal operations as shown in Figure 1.

Figure 1. Operational Scene of General Bulk Cargo Terminal.

3. Intelligent Perception of Mobile Machinery's Operational Status

3.1. Panoramic Imaging

Panoramic imaging first captures images and converts them into two-dimensional data. Then, pattern recognition is performed on the collected images, using image-matching algorithms to identify vehicles, pedestrians, obstacles, etc., during the driving process. Finally, the relative distance and relative speed between the target object and the mobile machinery are calculated based on the target object's motion pattern.

3.2. Millimeter-Wave Radar Perception

Millimeter waves are electromagnetic waves, and radar determines the distance between vehicles and objects by emitting radio signals and receiving reflected signals. Millimeter-wave radar operates at a frequency of 30–300 GHz, with wavelengths ranging from 1–10 mm, placing it between centimeter waves and light waves. As a result, millimeter waves combine the advantages of microwave guidance and electro-optical guidance. Millimeter-wave radar can detect objects at distances ranging from 30 to 100 meters. It is not affected by weather conditions and can operate normally even in the most adverse weather and lighting conditions [5]. It has a strong ability to penetrate smoke, offering all-weather, all-time operational capabilities, with a long detection range and high detection accuracy.

3.3. LiDAR Perception

LiDAR (Light Detection and Ranging) is an advanced optical remote sensing technology that emits a laser beam toward the target and determines the actual distance to the target object based on the time interval of the reflected laser received. Due to the high energy density and good directionality of lasers, LiDAR can detect objects at distances greater than 100 meters. It is used to measure object distances and surface shapes, with measurement accuracy reaching the centimeter level.

3.4. Precision Localization

3.4.1. Satellite Positioning

Satellite navigation positioning is a radio navigation system that provides mobile machinery with all-weather location, speed, and time information. However, its positioning accuracy is limited. To reduce or even eliminate positioning errors, differential GNSS technology can be applied, effectively utilizing known position reference stations or mobile stations to calculate common errors and achieve high-precision positioning for mobile machinery, with accuracy down to the centimeter level.

3.4.2. Inertial Navigation Positioning

Satellite navigation, as a positioning method, has limitations such as low update frequency (around 10 Hz) and vulnerability to obstruction, making it unsuitable for complex operational environments of mobile machinery. Inertial navigation, on the other hand, does not rely on external information or radiate energy to the outside. It continuously provides three-dimensional positioning and orientation of mobile machinery based solely on the system itself.

3.4.3. High-definition Map

High-definition maps are a crucial support for the development of automated terminals [6]. They play an important role in accurate lateral and longitudinal positioning, obstacle detection and collision avoidance, steering and guidance, and other aspects. Accurate maps are essential for the localization, navigation, and control of mobile machinery, as well as for the safety of autonomous driving.

4. Design of the Intelligent Perception Terminal for Mobile Machinery

The intelligent perception terminal for mobile machinery at general bulk cargo terminals integrates technologies such as panoramic imaging, millimeter-wave radar, LiDAR, and precise localization to achieve intelligent perception of the machinery's operational status. The sensed data is input into the onboard processor for analysis and processing. Based on the data, collision avoidance decisions are made for the mobile machinery, followed by control of its speed, direction, and braking, as shown in Figure 2. The mobile machinery intelligent perception terminal includes panoramic cameras, millimeter-wave radar, LiDAR, positioning module, IMU, a controller, communication module, and other components. All hardware devices are connected to the core system via corresponding data cables. Based on the port mobile machinery-Loader, the intelligent perception terminal has been installed and arranged on it, as shown in Figure 3. The onboard system operates on the onboard computer and mainly includes the following functional modules:

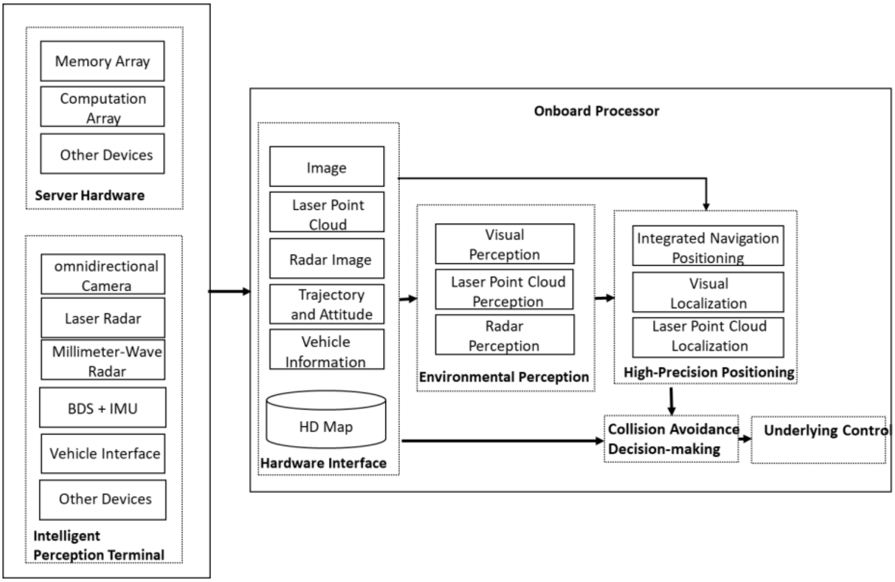

Figure 2. Schematic of the Intelligent Perception Terminal Architecture and Data Processing for Mobile Machinery

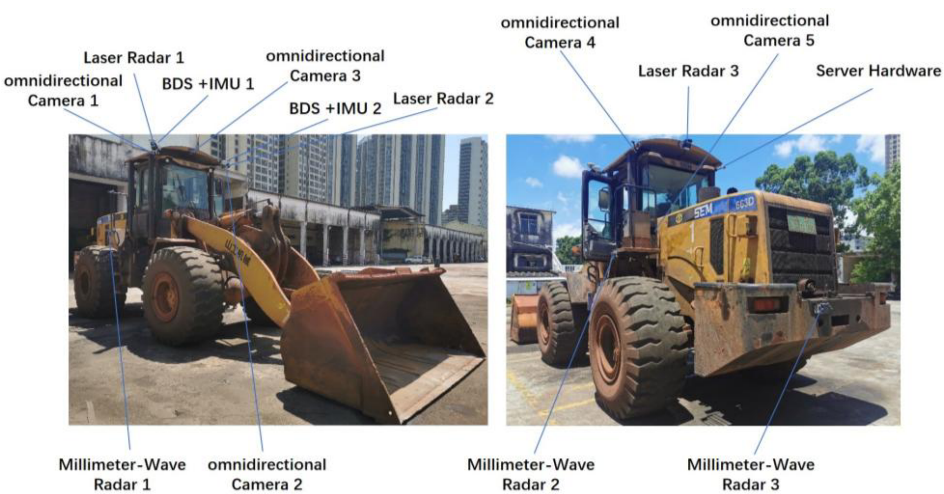

Figure 3. Installation diagram of the Intelligent Perception Terminal.

Environmental perception module: This module uses recognition models to identify the "human-machine-object-environment" interactions, generating a list of obstacles, including information such as the location, speed, and type of the targets.

Localization module: This module uses differential GNSS to detect the real-time position of the mobile machinery, and combines visual and laser-based local features obtained from the port area's environmental perception to perform map-based localization.

The panoramic camera, millimeter-wave radar, and LiDAR are installed within protective covers and connected to the onboard system via Ethernet. The GNSS (or GPRS) + IMU are connected to the onboard system via a serial port, while the mobile machinery itself is connected to the onboard system via the CAN bus. The HMI display is connected to the onboard system via Ethernet, and the results from various sensors and hardware devices can be displayed in real-time on the HMI. The onboard system and server system exchange data via a wireless network.

5. Conclusion

The key to port safety lies in the entire process of port loading and unloading operations, which is of significant importance in ensuring both the safety of port enterprises' assets and the lives of personnel. This paper focuses on analyzing the safety issues and causes of accidents in mobile machinery operations at bulk cargo terminals, studying intelligent perception technology for monitoring machinery's operational status, and designing an intelligent perception terminal for mobile machinery. The intelligent perception terminal enables the single-vehicle system to intelligently perceive people, objects, and the environment, providing support for multi-vehicle collaborative safety at the terminal, and playing a critical role in enhancing the safety of mobile machinery operations at the terminal. Based on the data collected and processed by intelligent perception terminals, the construction of a safety intelligent collision avoidance model and the development of a safety warning platform for complex operation areas of port mobile machinery will be carried out.

Acknowledgement

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Research on Safety Intelligent Monitoring Technology for Conveyor Belts in Dry Bulk Cargo Terminals

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Abstract. The port bulk cargo transportation system, involving long conveyor routes, diverse operational equipment, harsh environmental conditions, and numerous inspection points, is highly susceptible to various faults and damages over prolonged operation. The key challenges include conveyor belt misalignment, tearing, slippage, stacking, and material scattering, which significantly affect operational efficiency and safety. Traditional monitoring systems are limited by low real-time response, inability to operate in harsh environments, and inadequate failure prediction. This study proposes an intelligent conveyor belt safety monitoring system based on monitoring robots. The system incorporates advanced image processing, infrared thermography, and AI-based fault detection to enable 24/7 unmanned monitoring. This technology improves fault detection accuracy, operational efficiency, and emergency response capabilities. A comparative evaluation with existing monitoring systems highlights the superior performance of the proposed system, showcasing its higher accuracy, faster response time, and reduced operational costs.

Keywords: Bulk cargo conveying system, Conveyor belt, Monitoring robot, Intelligent monitoring

1. Introduction

As an important transportation equipment for dry bulk cargos such as coal and ores in ports, the conveying system has the advantages of large capacity, high efficiency, and economic benefits [1]. Conveyor systems are a cornerstone of modern bulk material handling, particularly in port terminals, mines, power plants, and factories. The design of these systems varies depending on the specific industry application. In ports, long-distance conveyor belts are used to transport bulk materials like coal, grain, and ore. These systems consist of several components, including the belt itself, pulleys, rollers, drive mechanisms, and tensioning devices.

Belt conveyors operate by continuously moving materials from one point to another. The conveyor belt moves over a series of rollers, powered by motors at one end of the conveyor system. The belt is typically made of materials such as rubber, fabric, or steel,

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depending on the application. These systems can transport large quantities of material over long distances, providing a reliable and cost-effective solution for material handling.

However, with their extended use, conveyor systems are subject to various operational challenges, such as misalignment, excessive wear, tears, and foreign object interference, local temperature rise and abnormal noise of equipment, which can lead to significant operational disruptions and downtime. and even cause local high temperature of the belt, leading to combustion and coal mine accidents [2-5]. In September 2020, a conveyor belt fire accident occurred at Songzao Coal Mine in Chongqing, resulting in 16 deaths and 42 injuries [6]. In June 2022, a worker in Fangchenggang accidentally got caught in a conveyor belt while cleaning up cargo leakage from the conveyor equipment, causing one death.

This research is to propose an intelligent monitoring system based on monitoring robots that will address these challenges such as conveyor belt deviation, conveyor belt tearing and edge tearing, conveyor belt slippage, conveyor belt stacking and scattering, and pipe belt machine failures and enhance the overall efficiency of conveyor belt systems.

2. Requirement analysis of conveyor belt safety intelligent detection system

2.1. Analysis of main fault types in the use of conveyor belt

Conveyor belts, especially in industries such as mining, ports, and manufacturing, face numerous challenges related to their maintenance and operation. The primary issues include:

Misalignment: Conveyor belts can become misaligned due to excessive load, mechanical failure, or environmental factors. Misalignment can lead to inefficient material transport, excessive wear on the belt, and even damage to the rollers and pulleys.

Tearing and Wear: Over time, conveyor belts are subject to tearing or wear due to the continuous transport of heavy materials. These issues can lead to disruptions in the system and the need for costly repairs.

Slippage and Overheating: Slippage occurs when the conveyor belt moves at a slower rate than intended, often due to high loads or poor friction. Overheating can also cause degradation of the belt material, further exacerbating wear and the risk of system failure.

In light of these challenges, existing monitoring methods, such as manual inspection and traditional sensor-based monitoring, have limitations in providing real-time, accurate, and reliable fault detection.

2.2. Traditional monitoring methods and their limitations

Traditional methods for monitoring conveyor belts primarily rely on manual inspections and mechanical sensors. Manual inspection involves periodic checks by operators to visually detect faults such as tears, misalignment, or spillage. However, this method is time-consuming, labor-intensive, and prone to human error, particularly in large conveyor systems with complex routes. Moreover, this approach cannot provide real-time feedback on system status, resulting in delayed fault detection and response.

Mechanical sensors, such as vibration sensors and pressure sensors, are often used to monitor the health of conveyor systems. Vibration sensors can detect abnormal vibrations associated with misalignments or mechanical failures. However, these sensors are often limited in detecting faults that do not cause significant vibrations, such as belt wear or slippage. Furthermore, environmental conditions such as dust, moisture, and temperature variations can interfere with sensor readings, leading to false positives or missed detections.

Thermal imaging and other sensor-based technologies have been used to monitor temperature changes in conveyor belts to detect overheating and excessive friction. While these technologies can detect some issues, they are often ineffective in harsh environmental conditions or in the presence of excessive dust, which can obscure readings.

2.3. The need for intelligent monitoring systems

Given the limitations of traditional methods, there is a growing need for more advanced and reliable monitoring systems. Intelligent monitoring systems, powered by artificial intelligence (AI), image processing, and robotic technologies, offer the potential to revolutionize conveyor belt monitoring by providing real-time, automated, and highly accurate fault detection. These systems can detect a wide range of faults, including misalignment, tears, slippage, and overheating, and can respond in real-time to prevent system failures. Additionally, the integration of AI and machine learning allows the system to learn from past data and continuously improve its detection accuracy.

3. Conveyor belt monitoring technologies

3.1. Overview of conveyor belt monitoring technologies

The evolution of conveyor belt monitoring technologies has been marked by a gradual shift from manual inspection to more automated systems that utilize sensors, cameras, and advanced data analytics. Below, we review some of the key technologies used in conveyor belt monitoring.

Visual Inspection Systems: Traditionally, visual inspection systems have been used to monitor conveyor belts. These systems involve human operators inspecting the conveyor belt for any signs of wear, misalignment, or damage. While manual inspection remains a common practice in many industries, it is time-consuming, labor-intensive, and prone to human error.

Vibration Sensors: Vibration sensors are commonly used to detect mechanical faults in conveyor systems, such as misalignment, bearing failures, and conveyor motor issues. These sensors can provide early warning signs of potential system failures. However, they are limited in detecting issues that do not produce vibrations, such as belt wear and minor misalignments.

Thermal Imaging: Thermal cameras are used to detect temperature anomalies in conveyor belts, such as excessive heat due to friction or mechanical failure. These systems can be used to monitor belt conditions continuously. However, thermal imaging can be affected by environmental conditions such as ambient temperature, humidity, and dust.

Acoustic Emission Sensors: Acoustic emission sensors detect the high-frequency sounds generated by cracks or fractures in the conveyor belt or related components.

These sensors can provide valuable information on the health of the system, but they require complex signal processing and can be sensitive to background noise.

Ultrasonic Testing: Ultrasonic sensors are used to detect defects and internal damage in conveyor belts [7]. These systems provide a non-destructive method for inspecting the condition of the belt, especially in hard-to-reach areas.

3.2. Difficulties in applying intelligent monitoring system to dry bulk terminal conveying system

While intelligent monitoring systems hold significant promise, there are several challenges in their implementation:

Environmental Interference: Conveyor belts operate in harsh environments, including high temperatures, dust, moisture, and vibration. These conditions can interfere with sensor readings, leading to inaccurate data or system failures. Advanced sensors and robust algorithms are required to overcome these challenges.

Data Processing and Integration: Intelligent monitoring systems generate large amounts of data from various sensors and devices. Processing this data in real-time can be computationally expensive and requires efficient data management systems. Additionally, integrating data from multiple sources (such as cameras, sensors, and robots) can be challenging.

Cost and Scalability: The implementation of intelligent monitoring systems can be costly, particularly for small or medium-sized operations. The cost of sensors, robotics, and AI software can be prohibitive. Moreover, scaling these systems to monitor large, complex conveyor systems requires careful planning and investment.

3.3. Advancements in intelligent monitoring technologies

The rise of intelligent monitoring systems has been facilitated by the development of machine learning, AI, and robotics [8]. These technologies enable automated systems to analyze data, detect faults in real-time, and provide actionable insights.

Machine Learning Algorithms for Fault Detection: Machine learning (ML) has emerged as a powerful tool for detecting faults in conveyor belts. ML algorithms can analyze large volumes of sensor data to identify patterns that indicate potential issues. These algorithms can be trained using historical data and continuously improve their performance over time.

Artificial Intelligence in Fault Diagnosis: AI-based fault diagnosis systems can automatically detect and classify faults in conveyor belts based on sensor data. AI algorithms can use techniques such as neural networks, decision trees, and support vector machines to classify faults and predict system failures.

Robotic Inspection Systems: Robots equipped with cameras, sensors, and AI algorithms can autonomously inspect conveyor belts and perform routine maintenance tasks. These systems can detect faults, capture high-quality images for analysis, and provide real-time feedback to operators. They can also reduce the need for manual inspections, increasing efficiency and safety.

IoT-Based Monitoring Systems: The Internet of Things (IoT) enables conveyor belts to be continuously monitored using a network of sensors that transmit data to a central system for analysis. IoT-based systems can provide real-time status updates, alerts, and diagnostics, allowing for faster response times and proactive maintenance.

4. The composition of conveyor belt safety intelligent monitoring system

The conveyor belt safety intelligent monitoring system is divided into two parts: data acquisition module and data processing module. Among them, the data acquisition module integrates a variety of types of sensors to collect data on the operation status of the conveyor; the data processing module is mainly used to process and analyze the data collected by the system, and to judge whether the conveyor belt system is faulty.

4.1. Sensor integration and data acquisition

The intelligent conveyor belt monitoring system proposed in this study integrates multiple sensor types to collect data on the conveyor's operational conditions. These sensors include high-resolution cameras, infrared thermography systems, vibration sensors, and environmental sensors. The data collected by these sensors is transmitted to a central processing unit, where it is analyzed using AI algorithms.

High-Resolution Cameras: These cameras capture detailed images of the conveyor belt, allowing for visual inspections of the belt's surface. The images are processed using image processing algorithms to detect faults such as misalignment, tears, and foreign objects.

Infrared Thermography: Infrared cameras are used to detect temperature variations on the surface of the conveyor belt, which can indicate issues such as excessive friction, overheating, or mechanical failure.

Environmental Sensors: These sensors monitor environmental factors such as temperature, humidity, and dust levels. The data from these sensors is used to adjust the sensitivity of the other sensors and optimize fault detection in varying conditions.

4.2. Data processing and fault detection

Once the data is collected, it is processed using advanced image processing and machine learning techniques to detect faults in real-time.

Image Processing Algorithms: The images captured by the high-resolution cameras are processed using edge detection algorithms, such as Canny edge detection and Hough transform, to detect misalignment and tears in the conveyor belt. The images are also analyzed for signs of wear, foreign objects, or other anomalies.

Machine Learning for Fault Detection: Machine learning algorithms, including decision trees and neural networks, are trained on historical sensor data to identify patterns indicative of faults. These algorithms are used to classify faults in real-time and predict potential system failures.

Real-Time Data Analysis: The system is designed to provide real-time feedback to operators, alerting them to any detected faults and providing recommendations for corrective actions.

5. Design and application of intelligent safety monitoring robot for conveyor belt

5.1. Design of intelligent safety monitoring robot

The monitoring robot is equipped with environmental monitoring sensors, a 360 degree binocular gimbal (including visible light cameras and infrared thermal imagers), a two-way voice system, an audible and visual alarm system, an intelligent auxiliary unit, etc. It has functions such as dust prevention, moisture prevention, and corrosion prevention, and can monitor the working environment, equipment noise, cargos foreign objects, and personnel safety. The monitoring robot is designed according to explosion-proof requirements to cope with various complex environments, as shown in Figure 1.

Figure 1. Physical diagram of monitoring robot.

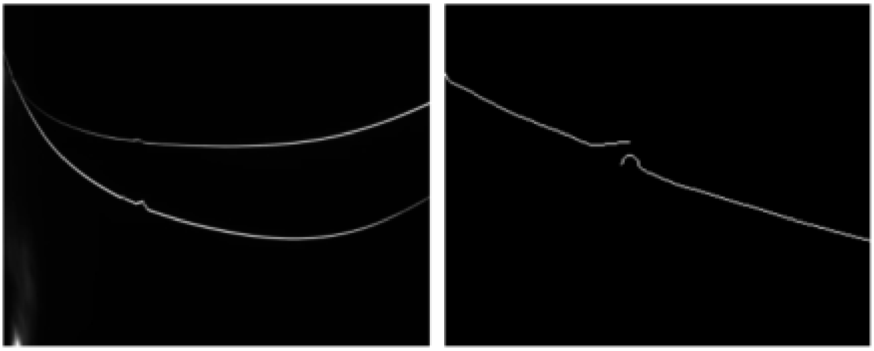
5.2. Application of intelligent safety monitoring robot

5.2.1. Monitoring of conveyor belt deviation. The visible light camera mounted on the monitoring robot captures video footage of the conveyor belt, extracts effective area images based on the collected video images, and processes the conveyor belt edge position using image processing techniques such as grayscale processing, Canny edge detection, and Hough line detection. The edge position of the conveyor belt is compared with a set threshold, and when the edge position of the conveyor belt exceeds the threshold, it is judged that the conveyor belt is off track.

5.2.2. Longitudinal tearing and edge monitoring of conveyor belt.

(1) Longitudinal tear monitoring of conveyor belt.

When the conveyor belt is longitudinally torn, due to the support of the rollers, the curvature of the torn part of the conveyor belt in the direction perpendicular to the running direction will change significantly. Based on this characteristic, within the field of view of an industrial high-speed CCD camera, a monochromatic thin line perpendicular to the direction of the conveyor belt is formed on the lower surface of the conveyor belt. The thin line will scan various parts of the conveyor belt surface as it moves. In the non-torn area, the laser line is approximately in a straight-line state; At the tear site, the laser line will bend or even break (as shown in Figure 2), and at the same time, more than one straight line and corner point with different slopes will be detected (i.e. the point where the brightness changes rapidly or the curvature reaches its maximum value), thus achieving the monitoring of the conveyor belt tear.



(a) Intact belt (b) Longitudinal torn belt

Figure 2. Comparison of conveyor belt tear identification.

The longitudinal tear monitoring equipment for conveyor belts includes industrial high-speed CCD cameras, linear laser emitters, image processing units, and equipment brackets. Due to the difficulty of capturing clear images with conventional cameras during conveyor belt operation, an industrial high-speed CCD camera is required for image acquisition (as shown in Figure 3). The linear laser emitter uses a red laser source with a wavelength of 650 nm. The emitted red point light source is refracted and imaged by a Powell prism to ensure uniform brightness distribution of the entire line of projected laser stripes, producing clear and uniform red laser stripes. The image processing unit implements real-time image computation and can support real-time processing of multiple images.

Figure 3. Longitudinal tear monitoring equipment for conveyor belt.

(2) Tape tear edge detection.

When the conveyor belt has torn edges, there will be gaps at its edges, and edge defects can be monitored through image monitoring to achieve torn edge monitoring. Due to the dim light below the conveyor belt, a strip LED light source is used to illuminate the area below the conveyor belt surface for supplementary lighting in the image acquisition area. Use an industrial high-speed CCD camera to capture videos and capture corresponding edge area images, and perform image edge detection with the Candy algorithm. Further perform line detection to obtain the edge of the conveyor belt. At the same time, through the image dilation and contour detection, the maximum diameter of the contour area can be obtained, and combined with the straight edge, the tearing edge and its area monitoring of the conveyor belt can be achieved.

5.2.3. Conveyor belt speed and slip detection. A high-precision meter is installed at the edge of the conveyor belt, and the movement of the conveyor belt drives the meter wheel to rotate. With the assistance of the encoder and acquisition module, precise speed monitoring of the conveyor belt is achieved. When the conveyor belt speed is below the threshold, it is determined that the conveyor belt has slipped.

5.2.4. Cargos monitoring of conveyor belt machine.

(1) Cargos temperature monitoring
By marking the cargos conveying area with lines and saving the position, when the monitoring robot reaches the marked locations, the infrared thermal imaging instrument automatically monitors the temperature of the marked cargos in that area.
(2) Conveying capacity monitoring
By using the visible light camera mounted on the monitoring robot to capture video images, the logistics area on the conveyor belt is identified, and the conveying capacity of cargos within a fixed time period is calculated based on the area, thereby monitoring the conveying capacity of cargos.
(3) Cargos foreign object monitoring
The main reason for longitudinal tearing of conveyor belts is caused by foreign objects such as large pieces of gangue or iron entering the conveying process. By using the visible light camera on the monitoring robot to capture video images, and applying YOLOv5 target recognition training to monitor foreign object images, foreign object monitoring of cargos on conveyor belts can be achieved (as shown in Figure 4).

Figure 4. Conveyor foreign body monitoring results.

(4) Cargos scattering detection
Install a fixed camera at the edge of the conveyor belt and emit a laser beam in the vertical direction of the conveyor belt. Obtain the edge of the conveyor belt through edge detection, and obtain a fixed pixel video image on one side of the conveyor belt. Obtain the skeleton image of the laser line in the image through image processing. When there is no cargos obstruction at the conveyor edge, the skeleton line will be straight. Otherwise, the skeleton line will become twisted or broken, thus achieving the monitoring of conveyor belt scattering.

5.2.5. Monitoring of pipe belt machine malfunctions

(1) Distortion and anti-packet fault monitoring

When the conveyor belt is running normally, the edge position of the conveyor belt along the line is relatively fixed. An industrial high-speed CCD camera is used to extract video images of the core area. After image processing, if the disconnection exceeds a certain range, it is determined that the conveyor belt has distortion, reverse wrapping, and other phenomena.
(2) Monitoring of pipe collapse and expansion faults
The visual inspection system equipment can achieve monitoring of pipe collapse and expansion faults in the pipe conveyor. Using an industrial high-speed CCD camera to extract effective video images of the pipe conveyor area, and using image processing techniques such as grayscale processing, Canny edge detection, and Hough line detection, pipe conveyor edge detection is achieved. When the pipe conveyor is running normally, only one edge line appears in the video image. When multiple edge lines appear (as shown in Figure 5), it is determined that the pipe conveyor has collapsed or expanded.

(a) In normal condition (b) For expanding or collapsing pipes

Figure 5. Monitoring results of pipe collapse and expansion faults of the pipe conveyor.

5.3. Performance evaluation and experimental results

The intelligent monitoring system was tested in a real-world port terminal with an extensive conveyor belt system. The system was evaluated under a variety of operating conditions, including different weather conditions, environmental factors, and operational loads. The experimental setup included a combination of high-resolution cameras, infrared thermography, and vibration sensors installed along the conveyor belt.

The performance of the intelligent monitoring system was compared to traditional monitoring methods. The following metrics were used to evaluate the system:

(1) Detection Accuracy: The system's ability to accurately identify faults, such as misalignments, tears, and slippage.

(2) Response Time: The time taken for the system to detect a fault and alert operators.

(3) False Positive and False Negative Rates: The percentage of incorrect fault detections.

(4) Operational Efficiency: The system's ability to operate continuously without disruptions.

The results of the experiments demonstrated that the intelligent monitoring system outperformed traditional methods in all metrics.

6. Summary

With the advancement of safety science and technology, the traditional safety management model in ports can no longer meet the demands of smart and safe port development. Intelligent conveyor belt safety technology, based on monitoring robots, effectively addresses issues such as conveyor belt deviation, tearing, slippage, stacking, scattering, and pipe conveyor machine failures. It enables all-weather, unmanned monitoring and detection during the port logistics transportation process, significantly improving inspection efficiency and accuracy, while enhancing the system's ability to handle emergencies.

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Agro-Climatic Zoning Based on GIS Technology and Developmental Suggestions for Persimmon Planting in Beijing

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Abstract. Persimmon is one of the important traditional fruit trees in Beijing. This study aimed to classify the distribution of suitable persimmon-producing areas in Beijing using GIS (Geographical Information System) technology, incorporating climatic and geographic data from the region. It sought to identify the most suitable, suitable, generally suitable, unsuitable, and least suitable areas for persimmon cultivation in Beijing. Presently, the cultivation area for persimmon trees in Beijing is more than 6000 hectares, accounting for 4.81% of the fruit tree area in the city. Big Data analysis showed that persimmon trees in Beijing were mainly distributed in mountainous and shallow mountainous areas, including persimmon-producing areas in southwest Beijing, Eastern Beijing, and shallow mountains in north Beijing. Considering the low price of persimmon and minimal orchard benefit, this study suggests promoting the transformation and development of the persimmon industry in Beijing through innovative development mode.

Keywords: Agro-climatic zoning, Beijing, Big Data, GIS, Persimmon.

1. Introduction

The distribution of fruit trees and the yield and quality of fruits are closely related to the ecological environment. Important ecological environmental factors include climate (e.g., light, temperature, water, air, frost, and snow), topography (e.g., altitude, slope, and landform), soil (e.g., parent material, thickness, and texture), biology, society (e.g., cultivation and management, environmental pollution), and so forth [1, 2]. Various ecological factors influence each other and comprehensively impact the growth and development

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of fruit trees. Hence, determining the suitable planting areas for different fruit trees is of great significance [3, 4].

The persimmon tree is one of the important traditional fruit trees in Beijing [5, 6]. The local cultivation of persimmon trees is described in Fangshan County, Changping County, and Pinggu County Records compiled during the Wanli Period of the Ming Dynasty (1573–1620). Japanese sweet persimmon was introduced in the 1820s. Fuyu, Jiro, Junhe, and other sweet persimmon varieties were introduced in Japan in 1975, and more than 30 varieties were introduced from Shanxi, Henan, Zhejiang, and Hubei in China. At present, Mopan persimmon is the most cultivated variety, accounting for nearly half of the total [7]; the other varieties include August yellow, Chutou, Chutou flat, Huo, Jindeng, and Chutao persimmon. In 2020, the persimmon cultivation area in Beijing was 6044.5 hectares, accounting for 4.81% of the total area of fruit trees in the city. This study involved agro-climatic zoning of persimmon planting in the whole city based on GIS (Geographical Information System) technology using the ecological and production data in Beijing and put forward scientific suggestions to provide references for fruit tree production in Beijing [8].

2. Materials and Methods

This study used the meteorological data of surface meteorological observatories in 16 districts of Beijing from 1985 to 2015. The data included the average or extreme minimum values of meteorological elements such as monthly average temperature, extreme minimum temperature, monthly precipitation, and monthly sunshine hours. Geographic data from the National Basic Geographic Information Center, including the longitude, latitude, altitude, slope, and other data of Beijing, were also used. The grid data of longitude, latitude, and altitude were extracted using GIS technology [2, 3]. The meteorological and geographic data were refined by the interpolation method to make a fine grid map of $100 \times 100\ m^2$.

The literature review, expert interviews, field investigations, and other methods were used to determine the climatic needs of persimmon trees in Beijing and establish the climatic suitability zoning index system [9]. Each zoning index was weighted through expert scoring and weight analysis, and the algorithm of the persimmon climate suitability index was established. The mathematical statistics method was used to build a small grid calculation model of the zoning index based on GIS technology to realize the spatial continuous distribution of the zoning index, obtain the climate suitability index distribution map of persimmon trees in Beijing, and divide the suitability grade to form a refined climate suitability zoning map. Combined with the Big Data of the persimmon production survey, this study analyzed the distribution of the main persimmon-producing areas and proposed scientific suggestions for development.

3. Results and Analysis

3.1. Agro-climatic zoning of persimmon planting in Beijing

Extraction of zoning index. Beijing is generally suitable for persimmon growth. The zoning indicators were selected, and the suitable areas in Beijing were determined based on the climatic conditions and the actual production of persimmon in Beijing [4, 9]. The relevant indicators were not appropriate for evaluating the suitability of persimmon in China. The main ecological factors affecting the growth and quality of persimmon in Beijing were: annual average temperature, soil thickness, annual precipitation, and altitude. Specific indicators and scoring standards are shown in Table 1.

Table 1. Zonation indicators and scoring criteria for persimmon in Beijing.

Zonation indicator	Criteria	Persimmon score
Average annual temperature (°C)	≥11	30
	9–11	20
	7–8	15
	<6–7	5
	<6.5	0
Average temperature in January (°C)	>–7	15
	–7 to –8	10
	–8 to –10	5
	<–10	0
Slope gradient	0–6	20
	6–14	15
	14–22.6	5
	>22.6	0
Altitude (m)	0–60	5
	60–300	15
	300–500	10
	≥500	0
Soil thickness (cm)	>80	15
	50–80	10
	30–50	5
	<30	0
Annual precipitation (mm)	>650	15
	400–650	20
	350–450	15
	≤350	0
Soil texture	Clayey soil	10
	Loamy soil	15
	Sandy loam	10
	Sandy soil	5

3.1.1. Agro-climatic zoning of persimmon trees in Beijing

Based on the analysis results, the comprehensive evaluation values were divided into five grades: most suitable, suitable, generally suitable, unsuitable, and least suitable. As shown in Figure 1, the most suitable areas for persimmon planting in Beijing are mainly plain areas, shallow mountains, and hilly areas. The development of the fruit tree industry in China cannot compete with grain in principle, and persimmon cultivation is strongly adaptable. Hence, it is mainly developed in shallow mountainous areas, valley basins, and other suitable and generally suitable areas.

The most suitable production areas mainly include the central and eastern plains, the southern and southwestern plains, and the piedmont gentle land in the northern and western plains (Figure 1). The production area accounts for about half of the total area of the city and is mainly distributed in urban areas, where crops and fresh fruits are planted. The actual cultivation area for persimmon is not large. The altitude of this production area is generally less than 100 m, the average annual temperature is above 10° C, the frost-free period is more than 185 days, and the rainfall is mostly 550–600 mm.

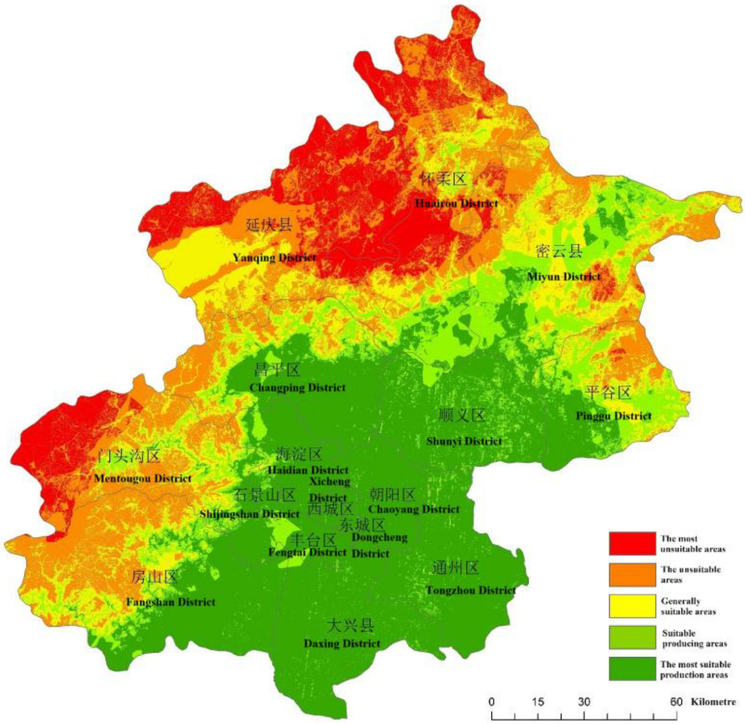

Figure 1. Distribution of suitable persimmon-producing areas in Beijing.

The suitable production areas mainly include shallow mountain areas in the west and north, hilly shallow mountain areas in the east, Miyun, Huairou, and Yanqing valley basins, Yongding River in Mentougou, and Dashi River in Fangshan. A majority of this area has shallow mountains, river valleys, or hilly areas, thus being the most important area for persimmon cultivation. The altitude of this production area is generally about 100–300 m, the average annual temperature is 8–10°C, the average temperature in January is higher than 6°C, the frost-free period is 180–185 days, and the rainfall is about 600 mm. Liu et al. also believe that the shallow mountainous areas of Fangshan and other places in Beijing have abundant solar and thermal resources, which are suitable for the growth of persimmon trees [10].

The generally suitable areas are the high-altitude areas in the west, north, or northeast, including some high-altitude basins in Yanqing. The mountainous areas with an altitude of 200–500 m have an average annual temperature of 6–8°C and a rainfall of 500–600 mm. Some places are influenced by microclimate, and the rainfall exceeds 650 mm. This area is also one of the main areas for persimmon cultivation; especially many old persimmon trees are distributed in the shallow mountains of Fangshan Valley.

The unsuitable areas are mainly mountainous areas with an altitude higher than 500 m, with an average annual temperature of less than 7°C; only a few persimmon trees are grown in this area.

The most unsuitable areas are mainly high-altitude mountainous areas. In Beijing, cultivating persimmon trees is difficult when the average annual temperature is lower than 6°C. The soil in high-altitude mountainous areas is often barren, lacking the basic conditions for planting persimmon trees.

3.2. General situation of persimmon production in Beijing

Persimmon tree is a traditional fruit tree species in Beijing. The cultivation area for persimmon trees was 6044.5 hectares by the end of 2020, accounting for 4.81% of the fruit tree area in the city. The total income was 37.69 million yuan, accounting for 1.04% of the total income from persimmon fruits. The persimmon-producing areas in Beijing are mainly distributed in Fangshan, Pinggu, and Changping. Fangshan District has the largest persimmon cultivation area of 2228.9 hectares, Pinggu District has 2052.8 hectares, and Changping District has 1153.8 hectares. Figure 2 shows the distribution ratio of persimmon trees in each district. Jinhai Lake is a township in Beijing with the maximum persimmon trees, with a total cultivation area of 464.8 hectares, followed by Zhang Fang Town (434.6 hectares), Liucun Town (365.3 hectares), Wangxinzhuang Town (323.9 hectares), Ming Tombs Town (330.1 hectares), Fozizhuang Township (279.5 hectares), and Hebei Town (222.9 hectares).

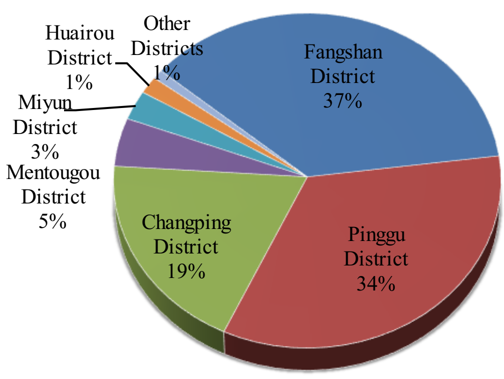

Figure 2. Distribution of persimmon cultivation areas in different districts of Beijing.

In 2020, the output of persimmon trees in Beijing was 26.0976 million kg, with Pinggu District having the highest output of 10.0343 million kg, followed by Fangshan District (7.049 million kg), Changping District (4.2 million kg), and Mentougou District (2.816 million kg). In 2020, the output value of persimmon trees in the city was 37.6908 million yuan, of which Pinggu District had the highest output value of 15.453 million yuan, followed by Fangshan District (7.4406 million yuan), Mentougou District (4.505 million yuan), and Changping District (4.2 million yuan). The output value distribution of each district is shown in Figure 3.

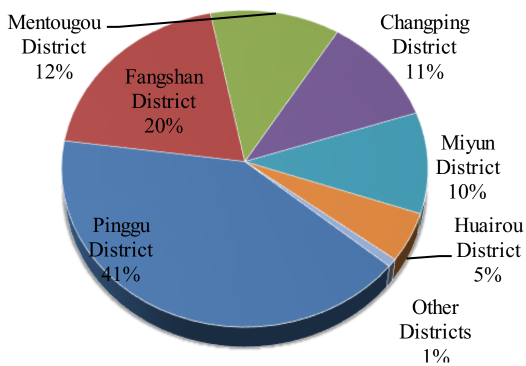

Figure 3. Distribution of persimmon output value in different districts of Beijing.

The age-wise area distribution map of different trees (Figure 4) showed that the maximum persimmon trees were aged 16–20 years, which were developed under the policy of "returning farmland to the forest" at that time. The young trees are few because of the low price of persimmon in the last 20 years. Also, some old persimmon trees aged more than 100 years are preserved because of the long life of persimmon.

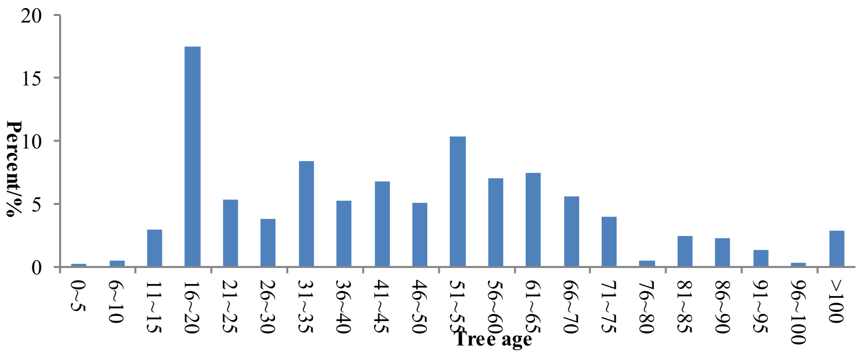

Figure 4. Age-wise area distribution map of persimmon trees in Beijing.

3.3. Distribution of main persimmon-producing areas in Beijing

Based on the survey of agricultural Big Data, we generated a distribution map of persimmon trees in Beijing. As shown in Figure 5, the distribution of persimmon trees in Beijing was mainly concentrated in the following three main production areas:

3.3.1. Persimmon-producing areas in southwest Beijing

These persimmon-producing areas are mainly located in Zhang Fang Town, Shidu Town, Qinglonghu Town, and Fozizhuang Township of Fangshan District in the warm front area of Nanshan Mountain in the west of Beijing. The persimmon cultivation area in this region is around 2000 hectares, accounting for 34% of the total persimmon cultivation area in the city. The cultivated varieties are mainly Mopan persimmon, besides a small number of pestle persimmon and Jindeng persimmon. Among these, Mopan persimmon is recognized as the best astringent persimmon variety in the world [11]. Mopan persimmon in southwest Beijing production area is the most prominent, with the largest cultivation area among all persimmon-producing areas in Beijing, among which Dayugou Village in Zhang Fang Town is known as "the first village cultivating Mopan persimmon in China."

3.3.2. Persimmon-producing areas in Eastern Beijing

These persimmon-producing areas are mainly distributed in Liujiadian Township, Dahuashan Town, Wangxinzhuang Town, Nandulehe Town, and Huangsongyu Township of Pinggu District. The total area is 2000 hectares, accounting for one-third of the total persimmon cultivation area in the city. The main varieties are August yellow, Mopan persimmon, pestle persimmon, and pestle flat and fire persimmon.

3.3.3. Shallow mountain persimmon-producing areas in northern Beijing

These persimmon-producing areas are mainly distributed in Changling Town, Shisanling Town, and Liucun Town of Changping District, with a total area of more than 1000 hectares. The cultivated varieties mainly include Mopan persimmon, August yellow persimmon, Chutou persimmon, and Huoshi persimmon.

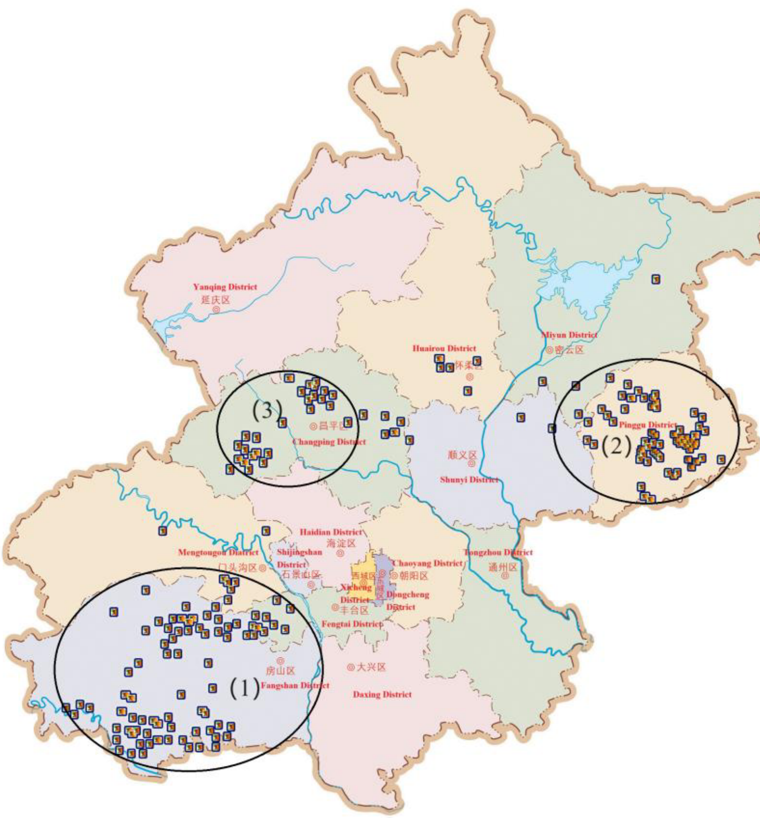

Figure 5. Distribution of persimmon-producing areas in Beijing.

Note: (1) Persimmon-producing areas in southwest Beijing. (2) Persimmon-producing area in Eastern Beijing. (3) Shallow mountain persimmon-producing area in northern Beijing.

3.4. Distribution of main persimmon-producing areas in Beijing

Persimmon is a traditional fruit tree species in Beijing. People have many misunderstandings about persimmon consumption at present [5]; therefore, the price of persimmon is extremely low, and selling it is difficult. Many persimmon trees in mountainous areas are actually in a laissez-faire state, and a large number of persimmon trees have died out. Taking Fangshan District, which has the largest cultivation area, as of 2020, the retained cultivation area is only 2228.9 hectares, a decrease of 70.9% from 7666.7 hectares in 2002; The output value of persimmons was 7.4406 million yuan, a decrease of 64.8% from 21.21 million yuan in 2002 [12]. Beijing should strengthen persimmon marketing and new product development, make consumers realize the nutritional value of persimmon, provide diversified products for consumers to choose from, and enhance the added value of products, to restore the development of persimmon industry in Beijing in the future. The characteristics of the three main persimmon-producing areas in Beijing and development suggestions are as follows:

Persimmon-producing areas in southwest Beijing. The production area is mainly located in the warm region in front of Nanshan Mountain in the west of Beijing, including Fangshan Zhang Fang Town, Shidu Town, Qinglonghu Town, Fozizhuang Township, and so forth. The cultivation area accounts for one-third of the total persimmon cultivation area in the city, and the cultivated variety is mainly Mopan persimmon. These areas are not only leads to the rapid accumulation of photosynthetic sub-stances but also makes fruits naturally deastringent, free of brown spots, and with a smooth peel, which is beneficial to improving the yield and quality [13]. Mopan persimmon in Fangshan has unique qualities such as early germination, late harvest, long growth period, high sugar content, high hardness, and strong storage and transportation compared with other suburban counties. Liu et al. also have similar research conclusions [10]. The Zhang Fang Mopan persimmon is the most famous, and some orchards have certain benefits. However, the development of the persimmon industry in this area still faces certain issues: low public recognition, small consumption of fresh food, great competition, low price, insufficient market expansion, and high production and circulation costs. Also, the production scale is small, and the industrialization level of persimmon is low [14]. Further, the industrial extension chain is short, and the main varieties are single. These are consistent with the conclusions of Zhang et al [15].

This study suggests driving primary production in the persimmon processing industry through secondary production, continuously extending the persimmon industry chain [16], developing new products (persimmon wine, persimmon vinegar, persimmon tannin powder, etc.), continuously tapping its potential economic value, excelling in persimmon brand publicity and construction, and enhancing brand value and public recognition. Further, the nutritional value of persimmons should be widely publicized using traditional sales methods and sales channels as well as innovative marketing models. The competitiveness of the production areas should be improved by organizing sightseeing activities and tourism and cultural festivals. Emphasis should be placed on organic cultivation management. The construction of an organic persimmon production base should be enhanced, and standardized management should be strengthened. Also, green and organic products should be produced to compete in the market. Some high-quality sweet persimmon varieties (Xincilang, Shanshiwan Yangfeng, etc.) can be introduced to optimize the variety structure and break the developmental limitation of its single variety. Wang et al. also believe that promoting the healthy development of the persimmon industry in the Fangshan area through unified organization and brand building [17].

Persimmon-producing areas in Eastern Beijing. This persimmon production area is mainly located in the shallow mountains and hills of Eastern Beijing, which are the most suitable and suitable distribution areas for persimmon. The cultivation area of persimmon is 2000 hectares, accounting for nearly one-third of the total persimmon-producing area in the city. The management level of this production area is high, with the greatest yield and benefit of persimmon trees in Beijing. The main problem is that the farmers give up persimmon management every year because of the low price, and therefore, the persimmon cultivation area is being reduced day by day.

The study further recommends improving the production management level, gradually eliminating or updating some poor-quality persimmon orchards, introducing high-quality persimmon varieties, developing excellent new varieties to meet multi-level consumption needs, and continuously strengthening the standardization construction of orchards. Also, sales methods and channels should be constantly innovated, and Big Data should be used to open up market sales and increase fruit prices. Further, efforts should be made to develop new processing varieties. Sightseeing and picking activities should be organized as much as possible, leisure and healthcare industries should be developed in mountain orchards, persimmon, and environmental resources in this production area should be fully developed and used, and fruit farmers in this production area should be assisted in increasing production and income. Furthermore, new information technologies such as Big Data should be used wisely to open up new circulation models, thereby reducing circulation costs. Moreover, it is required to adhere to the intensive road, stabilize the planting scale, establish a large-scale business model, gradually change the previous one-household business model, reduce production costs, and maximize profits.

Shallow mountain persimmon-producing area in northern Beijing. This persimmon-producing areas is mainly distributed in Changling Town, Shisanling Town, and Liucun Town of Changping District, with a total area of more than 1000 hectares. They are also the most suitable and suitable distribution areas for persimmon. The existing problems and suggestions for these areas are similar to those in the aforementioned two areas.

4. Conclusion

By conducting agricultural climate zoning based on GIS technology for persimmon tree planting in Beijing and systematically analyzing the future development issues of the persimmon industry, we have drawn the following main conclusions:

(1) The Beijing area is generally suitable for persimmon tree cultivation, with the main suitable areas located in the central and southern plains and warm mountainous areas.

(2) In 2020, the total area of persimmon trees in Beijing was 6044.5 hectares, mainly distributed in the warm and shallow mountainous areas in the southwest, east, and north of Beijing.

(3) Due to low persimmon prices and high production costs in recent years, the persimmon industry in Beijing has continued to shrink.

(4) It is recommended that in the future, the Beijing area promote the further development of the persimmon industry through the development of persimmon processing industry, brand building, and diversified orchard management.

Acknowledgements

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Exploration and Reflection on the Digital Transformation of Hydrological Monitoring in the Yangtze River in China

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Abstract. With the rapid development of information technology, the field of hydrological monitoring is undergoing a profound digital transformation. This paper discusses the application of digital technology in hydrological monitoring and its changes. By introducing advanced sensor technology, Internet of Things, big data analysis and artificial intelligence algorithm, the traditional hydrological monitoring method has been innovated, and the transformation from manual observation to automatic and intelligent monitoring has been realized. These technologies not only improve the efficiency and accuracy of data collection, but also enhance the ability to analyze and predict complex hydrological phenomena. In addition, the application of cloud computing platform promotes the centralized management and sharing of data, and provides strong support for cross-regional water resources management. This paper points out that the digital transformation of hydrological monitoring is of great significance for improving flood control and disaster reduction capacity and optimizing water resources allocation. In the future, it is necessary to further explore and improve the application of digital technology in the field of hydrology to meet the increasingly severe demand for water safety management.

Keywords: Hydrological monitoring; digitization; intelligent hydrology

1. Introduction

In today's era of information explosion and rapid technological development, we are in an unprecedented wave of digital transformation. With the wide application of new digital technologies such as cloud computing, big data and artificial intelligence, all walks of life are undergoing profound changes [1-4]. Digital transformation has not only changed the operation mode and business process of the organization, but also reshaped people's way of life and work.

The Hydrological Modernization Construction Plan of the Ministry of Water Resources emphasizes that the basic characteristics of modern hydrological system are the synchronization of technological progress with the development of the times and the matching of service capacity with the needs of the times. The Third Plenary Session of the 20th CPC Central Committee put forward for the first time to transform and upgrade traditional industries with digital intelligence technology, and digital intelligence has become an important engine for developing new quality productive forces. In recent

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years, Bureau of Hydrology, Changjiang Water Resources Commission, in accordance with the relevant arrangements of the higher authorities, proposed to use digital intelligence technology to empower the construction of intelligent hydrology and promote the digital transformation of hydrology [5].

Digital transformation is based on the digitalization, networking and intelligent upgrading of industries that need to be transformed, focusing on the construction of calculation data, algorithms and computing power, and realizing the digital intelligent upgrading of the whole business process, management process and service chain of this industry. The foothold is to enhance competitiveness and sustainable development ability, and build a modernization level that keeps pace with the times [6]. As the basic and pioneering work of hydrology, it is particularly important and urgent to carry out digital transformation of hydrological monitoring. By introducing advanced digital technologies and tools, the level of digitization, networking, and intelligence in hydrological monitoring is continuously improved, making hydrological monitoring safer in difficult to test or unmanned areas, more accurate in measuring large water depths and low flow rates in some reservoir areas, and more efficient in selecting data processing algorithms. This provides a higher quality and ubiquitous foundation support for the governance and protection of the Yangtze River Basin and the high-quality development of the basin's economy and society [7].

2. Construction Practice

In recent years, the Bureau of Hydrology, Changjiang Water Resources Commission has been committed to the digital transformation of hydrological monitoring, by optimizing station network layout, strengthening basic construction, and encrypting hydrological monitoring networks; Enhance sensing capabilities through "One station, One policy" to improve testing and reporting capabilities, as well as research and development of sensing equipment; Strengthen algorithm research, including satellite flow measurement, low water flow testing, AI-based flow estimation, and data processing methods; And developed hydrological data process platform, intelligent hydrological monitoring platform, and station digital twin platform. These efforts have significantly improved the accuracy and efficiency of hydrological monitoring, providing strong support for high-quality hydrological development. However, there are still shortcomings such as insufficient perception ability, insufficient data mining, and low level of intelligence. In the future, the Bureau of Hydrology, Changjiang Water Resources Commission will continue to make targeted efforts, overcome difficulties, and constantly innovate to better respond to challenges, accelerate the development of new hydrological productivity, fully integrate into the overall smart water conservancy construction, and showcase the new style of hydrological modernization construction [8].

2.1. Encrypted monitoring station network

2.1.1. Optimize the layout of the station network

According to the needs of the construction of "three lines of defense" for rainwater monitoring and forecasting, more than 20 hydrological stations have been built to promote the construction of storm surge monitoring and early warning center in the Yangtze River estuary, and the layout of the station network has been gradually improved.

Encrypting the hydrological monitoring station network can not only improve the accuracy of monitoring, reduce data errors caused by sparse stations, but also expand the coverage of monitoring, ensuring real-time and accurate monitoring of hydrological conditions in a wider area.

2.1.2. Strengthen capital construction

Since the "Thirteenth Five-Year Plan", more than 140 hydrological stations have been upgraded, and the level of infrastructure and technical equipment has been significantly improved. Up to now, 14 hydrological stations that are substantial in content, prestigious in reputation, and well-structured in form have been built. Hankou and Chenglingji Hydrological Stations were selected as the first batch of century-old hydrological stations of the Ministry of Water Resources in 2023.

2.2. Improve the perception ability

2.2.1. "One Station, One Policy" to improve the ability of forecasting

The self-recording rate of precipitation, evaporation, water temperature and water level reach 100%; On-line flow measurement technologies such as acoustic time difference method, acoustic Doppler method, fixed-point radar and side-scan radar have been put into use, and the on-line monitoring rate of flow is over 80%. The laser particle size distribution instrument has been put into full operation in the whole river, and the new equipment in sediment measurement, such as quantum dot spectral sedimentometer [9], has been put into use, and the sediment monitoring technology has made a major breakthrough.

2.2.2. Vigorously carry out research and development of perception equipment

A variety of sensing equipment, such as intelligent hydrological multi - parameter acquisition equipment, GNSS area rainfall meter, quantum dot spectral sedimentometer, quicksand integrated intelligent remote test system, water depth adaptive H-ADCP measurement and control system, double-track circulating radar flow measurement system, remote intelligent hydrological cableway, electronic field workbook for on - site hydrological monitoring and so on, have been successfully introduced, and the automatic perception ability of whole elements, whole process and all-weather has been continuously improved.

2.2.3. Continuously deepen the comparison of domestic instruments

We will carry out comparative tests of new instruments such as domestic ultrasonic time difference current meter, acoustic tomography flow automatic monitor, sailing ADCP and intelligent underwater laser sediment concentration meter, and fully promote the localization process of hydrological main measuring equipment.

2.3. Research on reinforcement algorithm

2.3.1. Research on satellite flow measurement method

Aiming at flood monitoring and large-scale flow perception, we put forward the satellite remote sensing flow measurement algorithm [10], the determination method of flow test reach, the reconstruction method of river section with satellite big data, the real-time water level estimation method coupled with multi-satellite information, and the flow estimation and data process method. It can explore and solve the problem of continuous measurement of river flow in no man's land, fill the gap of satellite flow measurement method based on river dynamics principle, and greatly improve the scope and density of river flow measurement.

2.3.2. Research on low water flow test method

Aiming at the common problem that it is difficult to measure small flow, especially for the water bodies with equal depth and low flow velocity in the reservoir area, the acoustic Doppler current profiler "navigation and fixed-point coupling algorithm" is proposed, that is, in the process of navigation flow measurement, the flow velocity is collected at a fixed vertical line in a time-integrated manner, and the total flow of the section is solved based on the numerical integration method, which solves the technical problems of flow measurement under such special water conditions. The research results have been incorporated into the national standards for river flow measurement, providing strong support for the Most Stringent Management System of Water Resource.

2.3.3. Research on AI-based flow estimation method

In the form of two-wheel drive of hydrological cause analysis and AI pattern recognition, intelligent algorithms such as Ridge, SVM and XgBoost are selected, and the AI-based flow estimation model is established based on more than 50,000 training samples, and the hyperparameter is optimized by Grid Search) + and Leave-One Out Cross Validation [11]. The practical application of Hankou Hydrological Station shows that both the modeling accuracy and the generalization accuracy have reached the level of the first-class precision station, which provides an important support for the water information flood in 2024. The research results have high popularization value and can provide scientific reference for the intelligent upgrade of hydrological station business.

2.3.4. Research on AI data process method

Manual alignment depends on the experience of a large number of data processors, who need to manually determine different influencing factors to select the data process algorithm, which has low automation and efficiency. Using artificial intelligence algorithm, an intelligent identification method of influencing factors of alignment is proposed. The data process method is automatically selected by AI, which has a high degree of automation. After verification by Hankou Hydrological Station from 2018 to 2020, the determination coefficients of AI data process methods are all above 0.9950, and the average relative errors are all within 3%.

2.4. Business platform for research and development

2.4.1. Hydrological data process platform

The research and development history of the Yangtze River hydrological data process platform has been more than 50 years. Since 1970s, after many iterations and updates such as DOS version, stand-alone version and network version, the hydrological data online process system based on B/S architecture was officially launched in 2020, and it was successfully selected as the outstanding case of "intelligent water conservancy should be proceeded first" that year, and the hydrological data process work moved from "daily settlement" to "real-time intelligence".

Platform features:

(1) A more professional data process method. Based on the Code for Hydrologic Data Processing, it provides a complete data process method library, which is suitable for all kinds of water conditions in the north and south, and can be popularized and applied nationwide.

(2) Better user experience. The system has friendly interface and stable operation. In particular, it provides a flexible, diverse, intuitive and accurate interactive Web relationship curve alignment function, which provides a "sharp weapon" for efficient compilation of hydrological data.

(3) More comprehensive quality management. Provide an open review platform, based on configurable expert rules and intelligent rationality analysis and inspection mode, and interactively review hydrological data online to ensure accurate and reliable results.

(4) More convenient output of results. Provide one-click standard typesetting and automatic compilation of hydrological yearbook, and get through the "last mile" of hydrological test product production.

2.4.2. Intelligent hydrological monitoring platform

The traditional hydrological measurement methods are complicated (the methods in different river sections are quite different, even "One Station, One Policy"), the process control is strict, and there are many isolated information (many elements+many small softwares, uneven development, especially there are many different hardware), and the measurement informatization is a "hard bone" with little progress for many years. In order to fill the information gap in the whole process of hydrological testing, after years of preparatory work, the Bureau of Hydrology, Changjiang Water Resources Commission has built an intelligent hydrological monitoring platform after three years of tackling difficulties from 2020. The system has achieved digital transformation and upgrading of various business processes in hydrological monitoring through standardized testing methods, process-based testing management, and integration of various isolated information. It has been successfully selected for the 2023 Mature and Applicable Water Conservancy Science and Technology Achievement Promotion List by the Ministry of Water Resources.

Platform features:

(1) All-factor test calculation: realize the algorithm abstraction and encapsulation of all factors and various test methods, automatically complete the analysis and calculation of hydrological test, avoid gross errors caused by manual calculation, initially realize paperless test, and greatly improve the accuracy and efficiency of test results.

(2) Full-process online management: two major data streams, manual observation and automatic monitoring, are automatically collected, and links such as recording, calculation, analysis, data processing, review and assembly are penetrated, so as to realize all-weather online management of hydrological monitoring business.

(3) Full-dimensional data display: visualization of multi-dimensional information such as hydrological station network, test tasks, instruments and equipment, original data and compiled data. In particular, the well-designed visualization module of station data

can complete all business functions and information query of a single station in one interface.

2.4.3. Digital twin platform of hydrological station

Since 2023, in order to actively integrate into the overall situation of smart water conservancy construction, in accordance with the general requirements of "demand traction, digital empowerment, application first, and capacity improvement", the Hydrological Bureau of the Yangtze River Committee has made every effort to build the first batch of 11 digital twin hydrological stations, comprehensively build the "three lines of defense" for rainwater monitoring and forecasting measures for rainfall monitoring and forecasting, enhance the hydrological forecasting capacity of the national hydrological station network, show the new features of hydrological modernization, and accelerate the development of new hydrological productivity.

The Third Plenary Session of the 20th CPC Central Committee put forward for the first time to transform and upgrade traditional industries with digital intelligence technology, and digital intelligence has become an important engine for developing new quality productive forces. Compared with the high standard of developing new quality productivity, there are still some shortcomings and deficiencies in the digital transformation of hydrological monitoring. In terms of perception, the monitoring ability of excessive flood and low dry water is insufficient, and the online monitoring ability of sediment and other factors is still insufficient; In data mining, hydrological data is not deeply processed and the data potential has not been fully activated; In terms of intelligence, the application of new quality technologies such as artificial intelligence and big data is not enough, and the level of intelligence of business is not high; All this requires targeted efforts, item by item, overcoming difficulties and continuous innovation in future work to better cope with more challenges.

3. Promotion Plan

At the present, Bureau of Hydrology, Changjiang Water Resources Commission will take multiple measures to fully promote the digital transformation of hydrological monitoring and promote the high-quality development of hydrology through "strengthening the foundation, practicing internal strength and grasping the ground".

3.1. Strengthen the foundation of hydrological data

Further consolidate the calculation basis and "strengthen the foundation" for the digital transformation of hydrological monitoring.

3.1.1. Remote sensing hydrological perception

Promote the application of satellite flow measurement technology, actively establish close cooperation with top domestic scientific research institutions and universities, explore and optimize the overall solution of river flow monitoring based on remote sensing technology by sharing data resources and jointly carrying out scientific research projects, and establish remote sensing hydrological stations to continuously improve the flow measurement level of excessive floods and no-man's land.

3.1.2. Rapid measurement technology for suspended sediment

Firstly, promote the rapid measurement of single-point sediment concentration meter, strengthen data quality control by using AI technology, improve the accuracy level of single-point sediment test, continuously optimize the test software, and save the links of water intake, drying and weighing to realize rapid sediment measurement. Secondly, promote the research of domestic ADCP rapid sediment measurement, carry out field comparison test, and combine advanced data processing technology and algorithm to study and establish methods and equipment for monitoring sediment transport flux.

3.1.3. Non-contact sounding

In view of the instability of river section and the difficulty in grasping the shape of breach, it is necessary to further study the methods of non-contact sounding. This kind of sounding method can avoid the potential safety hazard and operation difficulty existing in traditional measurement methods, and improve the accuracy and efficiency of measurement.

3.1.4. UAV + unmanned ship linkage

Strengthen the ship-machine linkage, improve the adaptability of cooperative work in the field, build an unmanned ship with multiple functions such as autonomous cruising, automatic obstacle avoidance and automatic docking, realize the voyage test of high-frequency hydrological factor flux, and solve the technical problems that it is difficult to monitor hydrological factors online under complex water flow conditions (such as the online flow monitoring of Hukou Hydrological Station).

3.2. Iterative intelligent algorithm

Further iterate the intelligent algorithm to "practice internal strength" for the digital transformation of hydrological monitoring.

Iteratively upgrade the existing AI-based flow estimation model. On the one hand, it is necessary to extend the training samples and conduct incremental learning on the existing AI models; On the other hand, according to the training effect, it is necessary to fine-tune the existing AI-based flow model structure in time to further improve the estimate flow accuracy and stability of the model.

Develop AI-based flow estimation model based on deep learning [12]. Further explore the use of multi-layer perceptron (MLP) [13], convolutional neural network (CNN) [14, 15], recurrent neural network (RNN) [16], Autoencoder, residual network (ResNet) [17, 18] and other deep learning technologies to integrate with traditional hydrological technologies, to further explore and improve the precision level of AI-based flow estimation flow.

Promote the application of AI in suspended sediment monitoring. Explore the use of AI technology to improve the conversion accuracy between single-point sediment measurement and cross-section sediment measurement, and expand the accuracy of estimating the average sediment concentration of cross-section by various existing single-point sediment measurement instruments. The AI-based suspended sediment estimation model is established, and the average sediment concentration in the section is directly calculated by taking the turbidity, water level and flow rate as driving factors.

Deepen the application of large model [19] in the field of hydrological monitoring. In addition to optimizing the functions of the big model in intelligent question and answer, file management, report generation, etc., it is also necessary to build a station agent, further strengthen the field knowledge learning of the big model in hydrological monitoring, enrich its vector database, and make real-time linkage with other systems to form a new decision support model with artificial intelligence as the core.

3.3. Building a smart engine

Developed a new-generation smart hydrological engine to propel digital transformation with tangible implementation in hydrological monitoring.

Based on the intelligent hydrological monitoring platform and hydrological data process platform, we will develop a unified, standard, and efficient digital intelligent platform for hydrological monitoring in the Yangtze River, so as to improve the digital, networked and intelligent level of hydrological monitoring. Firstly, adopt a cross - platform technical architecture. Using pure java language and technology stack made in China, the native business system is developed, which can run on X86 architecture or Linux environment to realize multi-platform compatible operation. Secondly, adopt a microservice based infrastructure. Using the micro-service architecture, the existing functions are disassembled and decoupled to form a data platform, a model platform and an application platform, which can realize the combination and collocation of building blocks. Data platform includes data governance, data mining, data application, etc. The model platform includes mechanism model, intelligent model and knowledge engine. The application platform provides the whole business chain application of hydrological monitoring. Thirdly, provide multi-level service requirements. The Yangtze River hydrological monitoring digital intelligence platform, which meets the three-level service requirements of hydrological testing, technical management and leadership decision-making, is forward compatible with testing software and field terminals of various survey bureaus, and backward supports business systems such as forecasting and dispatching, water resources management, etc., making the platform a "good tool" for testers, a "good assistant" for managers and a "good secretary" for decision-makers. The fourth is intelligent business applications. Deepen the integrated application of AI technology and large model technology, and create a series of intelligent business applications such as survey layout, data process of intelligent routing, intelligent quality control and data deep mining.

4. Summary

With the help of high-quality innovation platforms such as the China Committee of the International Hydrological Science Association, the Special Committee on Intelligent Hydrology and the Innovation Team of Bureau of Hydrology, Changjiang Water Resources Commission, the Bureau of Hydrology, Changjiang Water Resources Commission, will strengthen the learning, introduction, digestion and absorption of new quality technologies, actively cultivate new quality talents who are proficient in monitoring business and familiar with intelligent technologies, fully realize the digital transformation of hydrological monitoring in the Yangtze River, and contribute high-quality hydrological monitoring power to promote the high-quality development of hydrological industry.

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Cross-Scale Attention Mechanism of FastMAD-UNet Enhances the Segmentation of Pneumonia CT

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Abstract. Pneumonia is one of the major diseases leading to high morbidity and mortality worldwide. Generally, it is necessary to segment the CT image to obtain the lesions, and clinicians can effectively judge and treat according to the lesions. As a classical deep learning model, UNet has shown great potential in medical image segmentation. However, the recognition ability and segmentation speed of UNet in complex lesion areas still need to be improved. In order to solve this problem, this study proposes a pneumonia CT image segmentation task model FastMAD-UNet based on MAD-UNet model, which aims to improve the accuracy and robustness of pneumonia CT image segmentation. The model is based on ResNet18 network to extract multi-scale features, and combines LightASPP, EfficientMFFM and LightAttention. FastMAD-UNet was superior to the traditional UNet and UNet ++ models and MAD-UNet model in several evaluation indicators. FastMAD-UNet has significant performance advantages in pneumonia CT image segmentation. This model shows a broad clinical application prospect and is expected to provide strong support for the accurate diagnosis and treatment of pneumonia.

Keywords. deep learning,FastMAD-UNet,CT image,Medical image segmentation

1. Introduction

Pneumonia is a major global health threat, especially endangering the elderly and immunodeficient groups, with over a million deaths per year (WHO) [1]. Early and accurate diagnosis and timely intervention are the keys to prevention and control. CT has become an important diagnostic tool due to its advantages of high-resolution multi-dimensional imaging. However, precise segmentation of the lesion area still poses challenges, especially when the morphology is complex and the boundaries are blurred. Efficient auxiliary tools are urgently needed to improve accuracy.

Deep learning promotes a breakthrough in medical image segmentation: UNet overcomes the lack of detail and boundary ambiguity of CNN with multi-scale feature

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fusion [2]; UNet++ strengthens cross-layer connectivity to improve feature fusion [3]. Attention UNet introduces the key regions of attention focus [4]. VNet and other models have remarkable effects, improve accuracy and efficiency, and help diagnosis and treatment [5].

Despite the success of UNet and its variants in processing CT images of pneumonia, limitations persist, particularly in the extraction and fusion of multi-scale features. This deficiency impacts the accuracy of identifying complex lesion regions, leading to potential mis-segmentation and suboptimal Dice similarity coefficients, especially in regions with blurred boundaries. Consequently, this study aims to enhance the efficiency and precision of pneumonia CT image segmentation by building upon the MAD-UNet architecture[6]. The proposed FastMAD-UNet incorporates a Light Atrous Spatial Pyramid Pooling (LightASPP) module, an Efficient Multi-scale Feature Fusion Module (EfficientMFFM), and a Light Attention mechanism to improve the extraction and fusion of multi-scale features. Furthermore, the model demonstrates enhanced accuracy in identifying complex lesion regions.

2. Method

2.1. Data sources

We selected and integrated 7 public datasets to construct a large-scale dataset of COVID-19 lung CT, including infection masks labeled by radiologists (lesions mapped to white areas), covering diverse lesion morphology distributions. Data supports model training and evaluation, and is open access (https://www.kaggle.com/datasets/maedemaftouni/covid19-ct-scan-lesion-segmentation-dataset/data).[7,8,9]

2.2. Algorithm Models

The MAD-UNet model is established on the basis of UNet. The original MAD-UNet consists of a multi-scale fusion module, a detail feature enhancement module, a CMSCA module and a deep supervision module [6]. Based on this, improvements are made. The improved model consists of three modules: LightASSP, LightAttention, and EfficientMFFM.

The overall structure of the FastMAD-UNet model follows the encoder-decoder structure of the traditional UNet model. In the decoder section, ResNet18 is used as the backbone network, and the global average pooling and fully connected layers of the original ResNet50 are also removed [10]. Then, the LightAttention module [11] is attached to each layer of features. By learning the weights of the channel dimension, capture the local spatial features; The bottleneck layer integrates multi-scale characteristics through the LightASPP and LightAttention modules. The decoder gradually restores high-resolution details through EfficientMFFM; The final upsampling module generates high-resolution segmentation results and adopts the attention mechanism to eliminate fuzzy boundaries. The structure of the FastMAD-UNet model is shown in Figure 1, and the structures of the Bottle Neck block and the Final Up sample block in Figure 1 are shown in Figure 2.

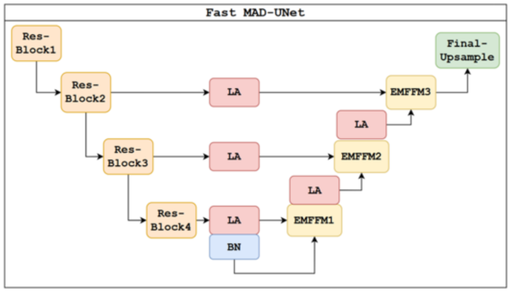

Figure 1. Model structure of Fast MAD-UNet. The BN in the figure represents Bottle Neck, and LA represents Light Attention.

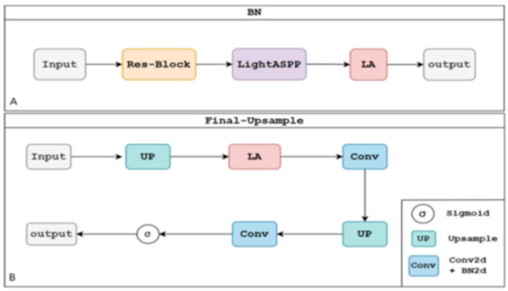

Figure 2. Construction of the Bottle Neck (BN) and Final-Upsample modules. Fig. 2A shows the layer structure of BN, and Fig.2B shows the layer structure of Final Upsample.

3. Result

The dataset of 2729 pneumonia cases (2500 positives) was divided into 2000 training cases and 250 validation/testing cases. The performance was evaluated by Dice, IoU and other coefficients, combined with the comparison between prediction and real masks (Figure 3) and the visualization of feature activation map (Figure 4) to reveal the decision-making basis of the model.

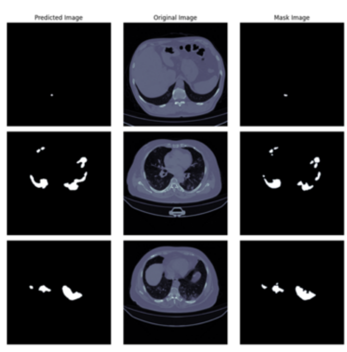

Figure 3. The image above is a comparison of images. Fig 3A is the segmentation result predicted by MAD-UNet. Fig 3B is the original image of the dataset, and Fig3C is the mask image corresponding to the dataset.

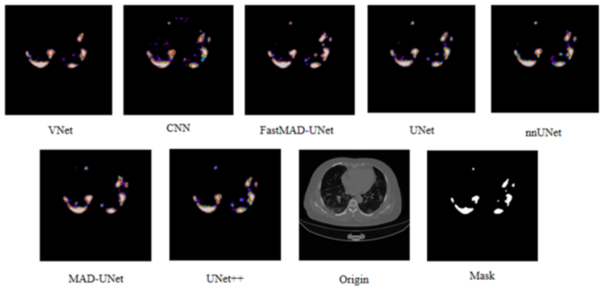

Figure 4. Each model feature activation map as well as the original and mask images.

The model adopts the joint tuning of weighted cross-entropy and Dice loss [12]. During training, FastMAD-UNet shows excellent convergence speed and robustness (Figure 5). In the comparative experiments on the NVIDIA GTX 1660 Ti/Intel i7-10700 platform, its Dice coefficient surpassed that of five models such as UNet and MAD-UNet (Table 1).

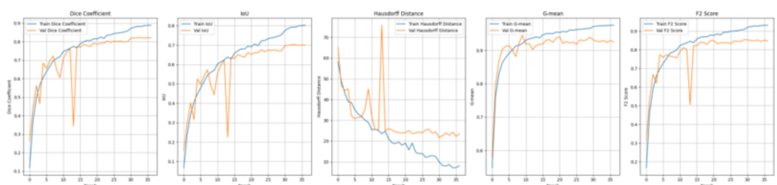

Figure 5. Dice, IoU, Hausdorff distance, G mean, and F2 score training and validation curves in FastMAD-UNet performance evaluation.

Table 1. Comparison of model performance and running time under the same hardware conditions for different models in the test set.

Net.	Dice.	IoU.	Sens.	Spec.	Acc.	G-mean.	F2.	Hausdorff distance.	Run time(seconds).
UNet	0.7236	0.5979	0.7966	0.9975	0.994	0.866	0.7663	19.8314	2096.2
UNet++	0.7287	0.6032	0.7936	0.9977	0.9941	0.8641	0.7662	19.0052	7190.1
nnUNet	0.7302	0.6064	0.8243	0.9973	0.9942	0.8824	0.7839	20.7124	2570.9
MAD-UNet	0.7008	0.5726	0.7775	0.9973	0.9935	0.8552	0.7422	23.3893	4964.14
CNN	0.6294	0.4922	0.7055	0.9971	0.9925	0.8055	0.6658	42.3135	740.2
VNet	0.5573	0.4236	0.6546	0.9966	0.9923	0.7486	0.6047	34.0163	5302.05
FastMAD-UNet	0.7309	0.6107	0.7894	0.9974	0.9939	0.8624	0.7619	21.8357	1840.88

4. Discussion

In order to ensure the efficient implementation of the pneumonia CT image segmentation task and reduce the vanishing gradient problem in the training process of the deep learning model, we used image scaling to uniformly scale the original size of the 512×512 CT image and its corresponding mask image to 256×256. Subsequently, the preprocessed data was input into FastMAD-UNet, and the training period was set to 100 for regularization training. Meanwhile, in order to balance overfitting and underfitting, we implemented the early stop method. After the model is output, the prediction mask is obtained through binarization.

It is worth noting that compared with MAD-UNet, FastMAD-UNet's parameters are reduced by 30% and the training time is increased by 62.9% (Table 1). However, when the model is used for image segmentation, the CMSCA module is removed from the model. The LightAttention module was changed to ensure that the segmentation accuracy of pneumonia CT images was not reduced. In Wyatt et al. 's study, AnoDDPM reduced the ability to deal with global noise, but significantly improved the segmentation accuracy of specific abnormal regions[13].

The core module of FastMAD-UNet is through four lightweight modules, ResNet18, LightASPP, LightAttention and EfficientMFFM, which significantly reduces the computational complexity while ensuring the segmentation accuracy [10,14,15]. LightASSP can enable the model to extract different scale information through different scales, and use void information with different void rates to extract the features of different sensory fields [16]. LightASSP uses 1×1 convolutional compression channels to replace the full connection layer, which reduces the number of branches and improves the computational efficiency compared with the traditional ASSP module [17,18]. Compared with CMSCA in MAD-UNet, LightAttention captures the feature association across regions [16], and adopts the combination strategy of channel compression and depth-separable convolution, which can reduce the computational burden while maintaining the sensitivity to the global [11,19]. Finally, LightAttention also uses residual structure to avoid feature degradation. To reduce the problem of gradient instability in model training. EfficientMFFM directly transfers details through shallow features, solves the dimension explosion problem caused by multi-scale feature redundancy and repeated feature splicing in traditional UNet hop [20,21], and improves the model discrimination ability.

5. Conclusion

This study achieved efficient segmentation of pneumonia images on seven datasets. The model effectively balanced accuracy and speed, and the lightweight design reduced the resource requirements. Subsequently, assessment indicators can be selected in combination with medical standards to assist doctors in formulating personalized treatment plans through lesion analysis.

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Design and Implementation of a Personnel Management System Based on Java EE

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Abstract. This study presents a Java-based personnel management system addressing inefficiencies in traditional methods through digital transformation. The system centralizes employee data management while integrating attendance tracking and leave processing modules. It emphasizes information security with dedicated privacy protection mechanisms. Implementation demonstrates operational cost reduction and workflow optimization, enhancing organizational efficiency and employee satisfaction. The research provides a practical framework for modernizing human resource management in enterprises using scalable Java technologies.

Keywords. java, personnel management system, information management module

1. Introduction

With the rapid development of information technology and the increasingly fierce global competition, enterprises and institutions are facing unprecedented management challenges[1].As one of the core elements of organizational operation, the efficiency and effectiveness of personnel management directly affect the competitiveness and development potential of the whole organization[2-3].Especially under the background of the continuous expansion of the organization scale and the increasingly complex business model[4], the traditional personnel management mode has been difficult to meet the needs of modern organizations for rapid response[5], decision support and accurate human resource management due to the limitations of manual operation, information island and data processing ability[6].

In order to effectively deal with these challenges, it is imperative to build a personnel management system based on advanced IT technology[7].This paper aims to explore how to use java and other cutting-edge technologies to design a personnel management system with comprehensive functions, excellent performance, safety and reliability[8], so as to meet the all-round needs of current enterprises and institutions for human resource management[9].The system can not only realize the digital and

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centralized management of personnel information[10-11], but also provide scientific decision support for the management through intelligent data analysis and prediction, so as to improve the overall operation efficiency and competitiveness of the organization[12]. The implementation of this system is expected to greatly optimize the personnel management process[13], reduce operating costs, and improve employee satisfaction and organizational performance [14-15].

2. Introduction to development environment and related technologies

2.1.MVC mode introduction

MVC (model view controller) is a software architecture mode, the workflow initiates with user requests routed through controllers, which invoke models for data processing. Results propagate back to views for presentation, enforcing strict separation of concerns. This pattern enhances code maintainability by isolating UI modifications from business logic changes, while promoting reusability through modular design. Its layered structure supports scalable system evolution, making it foundational for modern frameworks requiring clear responsibility partitioning.

2.2. Introduction to b/s architecture

The Browser/Server (B/S) architecture centralizes application logic on servers while enabling client interactions through web browsers, eliminating client-side software dependencies. Structured into three tiers—presentation layer for user interface rendering, logic layer for server-side processing, and data layer for database operations—it leverages HTTP requests and RESTful APIs for communication. Clients initiate requests via browsers, which web servers route to application servers. These servers execute business logic, interact with databases, and return JSON data for dynamic HTML generation, minimizing client computational load.

Key advantages include cross-platform compatibility (browser-only access), centralized data management for streamlined updates/security, and reduced maintenance through server-centric updates. Security is enhanced by confining critical operations to servers, while scalability derives from decoupled tiers enabling distributed cloud integration. Widely adopted in enterprise systems (e.g., HR platforms, e-commerce), B/S architectures support real-time synchronization, remote accessibility, and resource-efficient performance across devices. The model's server-side computational offloading ensures consistent user experiences despite heterogeneous client hardware, while RESTful API standardization facilitates interoperability with external services. By abstracting client requirements to browser standards, it reduces deployment costs and technical barriers, making it optimal for collaborative tools, IoT dashboards, and cloud-native applications requiring ubiquitous access.

2.3. Key features of the spring framework

This lightweight Java framework supports modular application development via dependency injection (DI) and inversion of control (IoC) for loose coupling. It enables

AOP to enhance functionality without code modification through interceptors/pointcuts and integrates MVC architecture for web layer separation. Spring abstracts data access (JDBC, Hibernate) and offers unified transaction management. It seamlessly integrates third-party tools (Struts, MyBatis) while promoting pluggable components, cross-platform compatibility, and streamlined enterprise application development through its container-managed object lifecycle and configuration simplicity.

2.4. Mybatis framework introduction

Mybatis is an excellent persistence layer framework that supports custom SQL, stored procedures, and advanced mapping. Mybatis eliminates almost all JDBC code and the work of setting parameters and obtaining result sets. Mybatis can configure and map primitive types, interfaces and Java POJOs (plain old Java objects) to records in the database through simple XML or annotations.

3. System analysis

3.1. System feasibility analysis

We believe that the b/s architecture based on java can better meet the needs of all aspects of software. In particular, open source web containers such as Tomcat have been adopted by many high demand systems because of their excellent performance in all aspects. The database part can rely on MySQL to read and store data. The hardware and software requirements of the system are easy to meet.

3.2. Economic feasibility analysis

The traditional pure manual management mode is prone to problems such as low efficiency, error prone, difficult management and difficult review, which is often easy to cause losses. However, the personnel management system using information technology, because of its characteristics of accurate data, easy maintenance, simple operation and easy expansion, fundamentally achieves the purpose of reducing the intensity of human operation and improving the accuracy of data. In addition, the research and development cost of the system is not high, and all kinds of small and medium-sized enterprises and institutions can accept it.

4. System design

4.1. Overall system architecture design

According to figure 1, the system can be divided into the following modules. organization management module, personnel management module, salary management module and personal information management module.

Figure 1 overall architecture design diagram

4.2. System database table design

According to table 1, the system uses MySQL database as data storage, and creates multiple database tables according to business requirements, mainly including user table, user role table, department information table, user department table, personnel job table, personnel leave table, personnel attendance table, personnel salary table, etc., as follows.

Table 1 database description and function description

Database table name	Chinese table name	Function description
Tb _User	User table	Basic information of login user, such as user name, password, role, etc
Tb _User _Role	User role table	User's corresponding permission information, etc
Tb _Dept	Department table	Information table all kinds of basic information of each department, such as department name, etc
Tb _User _Dept	User department table	Relationship between users and departments
Tb _User _Leave	Personnel leave form	Personnel leave application form information, such as dummy, reason, time period, etc
Tb _User _Wage	Personnel compensation	Remuneration items of each person, such as position salary, education bonus, assessment promotion, etc
Tb _Duty _Clerk	Personnel attendance sheet	Record personnel attendance information

● User table. The main fields of various user types in the storage system include index serial number, login name, login password, role permission type, and account expiration time. The index serial number is used as the primary key and unique identification of the table.

● User role table. Store the role information of each user and the permission information of various functions. Foreign key association is carried out through the user serial number of this table and the serial number of the user table. When carrying out various key operations, the relevant data in this table will be queried first to confirm the legitimacy of the operation, and then the key operations will be formally executed.

4.3. System function design

● Organization Management Module. This module manages enterprise organizational data through department, job, and personnel management. Create departments by defining name, description, and responsible personnel. Modify/Delete departments to reflect structural updates or removals. Query departments via name, head, or criteria for quick access. It ensures real-time alignment between system data and organizational changes while streamlining structural adjustments.

● Job management. This function maintains standardized role definitions through job creation (setting name, responsibilities, level, department), modifications (updating attributes), deletions (removing obsolete roles), and queries (filtering by name, level, or department). It ensures accurate alignment between job data and organizational needs while enabling efficient oversight of role structures and responsibilities.

● Personnel management. This module streamlines employee data management through employee addition (capturing personal/contact details, employment dates, department/job assignments), profile updates (adjusting personal/role data), deletions (removing inactive records), position transfers (reassigning roles/departments), and queries (filtering by name, department, or job criteria). It ensures real-time synchronization between system records and workforce changes while maintaining data integrity and enabling rapid access to employee details for operational or developmental adjustments.

A. New User System administrators exclusively handle user creation. Login validation redirects admins to the user addition interface, where ID numbers validate uniqueness. Existing IDs trigger re-submission prompts; new IDs enable direct registration. Non-admins are redirected to standard homepages.

B. User Info Modification Admins edit non-ID attributes (e.g., contact details, roles) while preserving immutable ID data. Access requires admin authentication, with unauthorized users redirected post-login checks.

C. User Info Query All users perform searches, but access tiers apply. Admins retrieve cross-departmental data, while standard users view only their department's records via filters (name, role).

D. User Deletion Admin-only removal mandates dual confirmation and audit logging. Unauthorized users are blocked, ensuring compliance with data integrity protocols.

● Personnel management module. This module mainly includes attendance management and leave management, according to figure 2, figure 3.

This module covers attendance management (tracking employee attendance records, generating time-specific or individual statistical reports, and compiling finalized results with approved leave data) and leave management (processing employee leave requests with reason/duration details and enabling department heads to review/approve submissions). Personnel staff oversee attendance analytics, while managers validate leave workflows to ensure compliance and operational continuity.

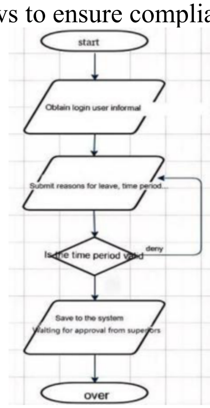

Figure 2 Leave inquiry chart

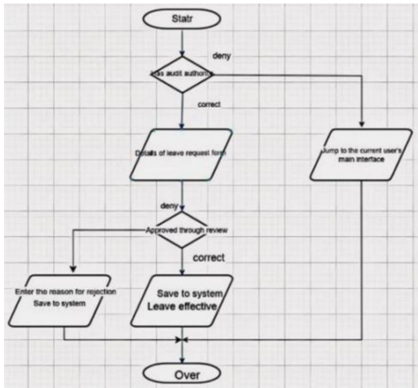

Figure 3 False bar audit chart

● Salary management module. This module centralizes salary system configuration (defining position/level-based compensation structures with base pay, allowances, and bonuses aligned to organizational policies and market standards) and payroll execution (automating wage calculations, approvals, and disbursements). Admins perform periodic salary adjustments to maintain market competitiveness and fairness, while employees access self-service portals to view salary breakdowns, historical changes, and downloadable payslips.

Payroll workflows integrate attendance, performance metrics, and deduction rules to auto-generate accurate payrolls. Post-calculation, admins review and approve payments before disbursement via flexible methods (bank transfers, cash). The system enforces compliance through audit trails and provides real-time payroll data exports for analytics. Employees verify earnings or print statements, ensuring transparency and reducing administrative overhead.

● Personal information module. This self-service portal centralizes access to attendance tracking (viewing records of late arrivals, absences, or overtime with date-based filters and export options), leave management (submitting online requests with type, duration, and reason details for supervisor approval, plus real-time status tracking), payroll insights (reviewing monthly/annual income, deductions, and tax breakdowns via encrypted, digitally signed payslips), and profile updates (editing contact details, emergency contacts, or uploading certificates/photos). Employees manage attendance data, streamline leave workflows, and verify earnings autonomously while ensuring HR records remain current and secure. Customizable approval chains and mobile/desktop access enhance flexibility, transparency, and compliance across personal data management.

5. System implementation

5.1. Database related parts

● Database connection. According to figure 4, In all kinds of information application systems, the management of database connection affects the overall performance and scalability of the system to a great extent. This system uses MySQL database to store system related data, and uses the inversion of control (IOC) function in spring framework to realize the specific implementation of database connection.

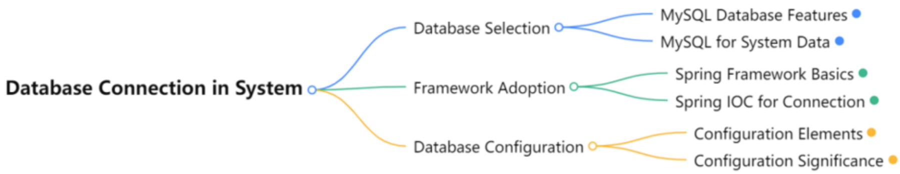

Figure 4 database related configuration

● Data access class (DAO). In order to balance security and performance, realize the separation of data access and business logic, and reduce the coupling degree between various modules of the system, we encapsulate the operations of adding, deleting, querying, and modifying database tables, and only provide the interfaces required for external access.

5.2. Log in

According to figure 5, When the user logs in, enter the login name and password. If the login name and password are correct, the system will authenticate, authorize and jump to the corresponding home page. If an error occurs, it will stay in the login interface and prompt the error message.

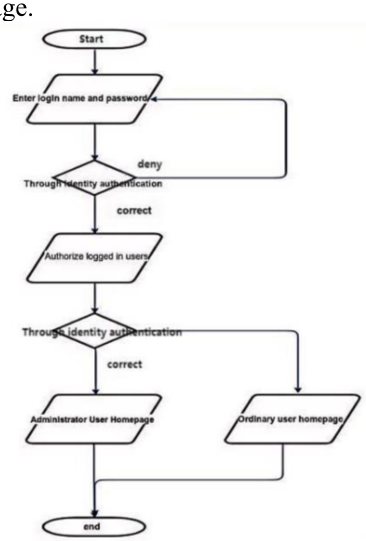

Figure 5 program flow chart

5.3. Organization management module

According to figure 6, This module is operated by employees of the personnel department, and is mainly used to maintain and update department information, position information and personnel information.

● Department management. The DeptService interface defines department operations, while DeptServiceImpl implements CRUD functions via native SQL, abstracting database interactions for efficiency. DeptBean encapsulates database data for JSP rendering, and DeptController handles UI interactions by invoking service-layer methods. DeptForm captures user query criteria, ensuring seamless data flow during execution. This layered structure enhances code maintainability, separates business logic from presentation, and streamlines department management workflows.

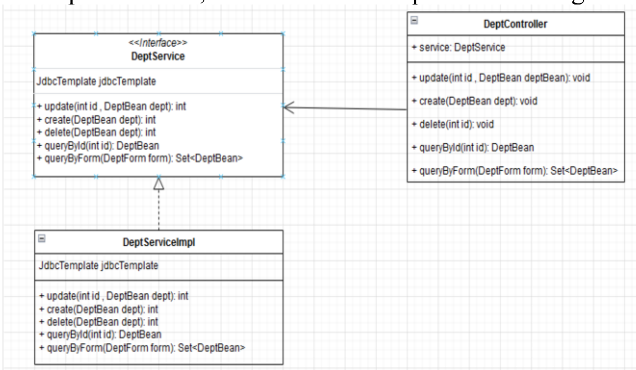

Figure 6 class diagram of department management module

● job management

According to figure 7, DutyService defines CRUD operations and database interaction protocols, while DutyServiceImpl executes them via native SQL for Dao-layer access. DeptDO maps database entities to JSP for data rendering, and DutyController processes UI-triggered actions by coordinating service-layer logic. This layered architecture separates business rules from presentation, ensuring scalable job management with clear code hierarchy.

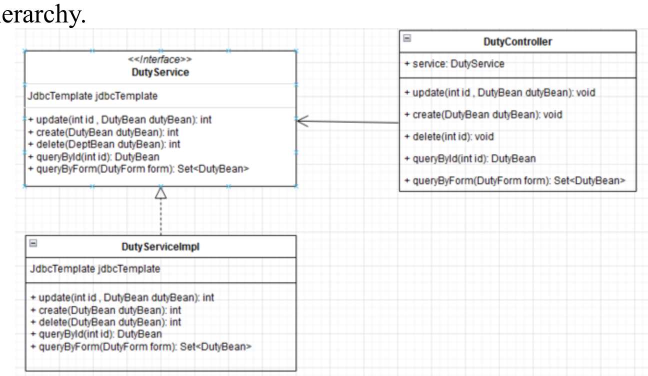

Figure 7 class diagram of job management module

● personnel management. DutyService defines CRUD operations and database interaction protocols, while DutyServiceImpl executes them via native SQL for Dao-layer access. DeptDO maps database entities to JSP for data rendering, and DutyController processes UI-triggered actions by coordinating service-layer logic. This layered architecture separates business rules from presentation, ensuring scalable job management with clear code hierarchy.

5.4. Personnel management module.

● personnel information. This module manages employee profiles (CRUD operations for personal/work details via form-based interfaces), attendance tracking (recording late/leave records with automated attendance rate calculations and salary deductions), and leave workflows (employee-submitted requests with type/duration and admin approvals). Features include data filtering, statistical exports, and role-based access to ensure accuracy and compliance across HR operations.

5.5. Salary management module

The salary management module automates payroll processing by integrating employee-specific data (base salary, performance metrics, allowances) with statutory deductions (taxes, social insurance) to generate monthly compensation statements. Personnel officers input monthly variable components like bonuses and subsidies, while the system aggregates gross earnings, subtracts mandatory withholdings, and calculates net pay through predefined algorithms. The payroll output formats employee compensation details systematically, including earnings breakdowns and deduction summaries, with PDF export capabilities for audit trails. Automated data integration enables seamless transfer to financial systems for organizational-level accounting and fund distribution. Permission-based access ensures payroll visibility aligns with hierarchical roles, maintaining confidentiality while streamlining verification workflows. This computational approach minimizes manual errors in multi-factor salary determination, particularly for complex compensation structures involving performance-linked variables.

5.6. Personal information management module

Realize the functions of viewing and modifying employees' personal information, including login password, contact information, home address, etc. Employees can update these information at any time in the system to ensure its accuracy and timeliness.

5.7. other modules (placeholders)

In actual projects, these parts should be replaced by specific module names and implementation details. For example, it can include salary management module, training management module, recruitment management module, etc. each module should have a clear realization goal and function description.

6. Conclusion

The Java-based personnel management system addresses inefficiencies in traditional models by leveraging modular architecture for scalability and multi-layered security protocols including authentication and encryption. Its concurrent access design supports multi-department collaboration, while comprehensive logging enables effective system monitoring and maintenance. Personnel management system enhances enterprise efficiency and quality while reducing labor costs and risks. It provides scalable technical support for future growth, with ongoing optimization aligned with digital transformation trends. The system's agile frameworks and intelligent features promote organizational evolution towards data-driven operations.

Acknowledgments

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Artificial Intelligence Based Electricity Payment Reminder and Control System and Method

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Abstract. The traditional electricity payment reminder adopts the "manual+SMS" method, and the reminder staff cannot optimize the reminder strategy according to the customer's service needs and payment habits, and can only passively execute the traditional reminder process. Therefore, this article proposes an artificial intelligence based electricity payment reminder and control system and method. Develop reminder strategies for different types of overdue users through credit rating analysis, analysis of overdue user characteristics, and analysis of electricity fee recovery risks, in order to reduce compliance risks and monitor overdue status in real time, and promptly identify potential default risks.

Keywords. electricity payment reminder, electricity marketing, debt collection strategy, owing status, intelligent delivery reminder

1. Introduction

The collection of electricity bills is the core work of power enterprises, which directly affects the economic benefits and operational stability of the enterprise, and is the ultimate manifestation of the enterprise's operating results [1]. But the country has high standards for the business environment, requiring companies to keep up with the times, not only focusing on economic benefits and improving power supply service levels, but also using differentiated delivery strategies to protect the rights and interests of customers, especially those related to people's livelihoods and key customers, and reduce public opinion and complaint risks.

Domestic and foreign scholars have conducted certain research on intelligent delivery reminders. The design and research of the intelligent voice electricity reminder system in reference [2] not only reflect high research value in the era, but also demonstrate strong practical feasibility research significance, achieving the goal of promoting the intelligent development of the power system. Reference [3] elaborates on the causes and influencing factors of electricity error rate in smart metering, and proposes optimization measures, including data collection and transmission optimization, algorithm optimization, calibration and inspection measures, and user training, to

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improve the accuracy and precision of electricity metering. Reference [4] designed and implemented an intelligent voice electricity fee reminder system using an end-to-end speech synthesis module based on Tacotron 2 and Griffin Lim algorithm, with Spring Boot as the main framework, combined with RocketMQ and WebSocket technologies, including automatic voice reminder function and user billing information management. Reference [5] innovates the management method of electricity bill verification and collection, carries out intelligent transformation, and finally achieves a new leap in electricity bill management. Reference [6] analyzes the application of intelligent electricity billing based on the new model of electricity billing. The traditional manual door-to-door method in reference [7] restricts the development of electricity payment reminder work and the collection personnel in practical work, making it complicated, repetitive, inefficient, and ineffective. Through information technology and intelligent means, achieve systematic, scientific, and modern management of electricity bills. However, traditional electricity payment reminders adopt a "manual+SMS" approach, and the reminders cannot optimize the reminder strategy based on the customer's service needs and payment habits. They can only passively execute the traditional reminder process. At the same time, the number of electricity customers is increasing year by year, but there is a shortage of personnel to urge payment of electricity bills, and the task of manual collection is heavy. The uneven level of business skills among fee collectors, inappropriate fee collection methods, and inappropriate frequency settings can easily affect customer satisfaction, create service complaint risks, and affect the image of power grid enterprises.

Therefore, this article proposes an artificial intelligence based electricity payment reminder and control system and method, which deeply analyzes user electricity consumption behavior and customizes differentiated reminder strategies and service plans for each electricity customer, achieving a transition from "one size fits all" to "precision". By using intelligent means to achieve automated and precise management of electricity bill reminders, the operational efficiency and management level of power grid enterprises can be improved.

2. Construction of an Artificial Intelligence based Electricity Payment Urgency Control System and Method

2.1. Entities Methods for Controlling and Urging Payment of Electricity Bills

Targeting diverse user groups and overdue situations, intelligent analysis technologies such as credit rating, analysis of overdue user characteristics, and risk analysis of electricity bill recovery are used to accurately match personalized reminder strategies and automatically generate reminder task orders. Subsequently, the reminder process was efficiently executed through various channels such as automated outbound calling system, SMS reminders, voice broadcasting, and manual intervention. For example, for long-term overdue users, measures such as door-to-door collection and legal litigation can be taken; For occasional users who owe fees, they can be reminded to pay in a timely manner through SMS, phone calls, and other means; For users who often forget to pay, more frequent reminders can be set up; For users with poor credit records, stricter reminder measures should be taken. At the same time, through on-site visits, user feedback, and other methods, complete customer on-site electricity usage information, collect user opinions and suggestions on electricity payment services, and continuously improve and optimize services. The business architecture is shown in Figure 1.

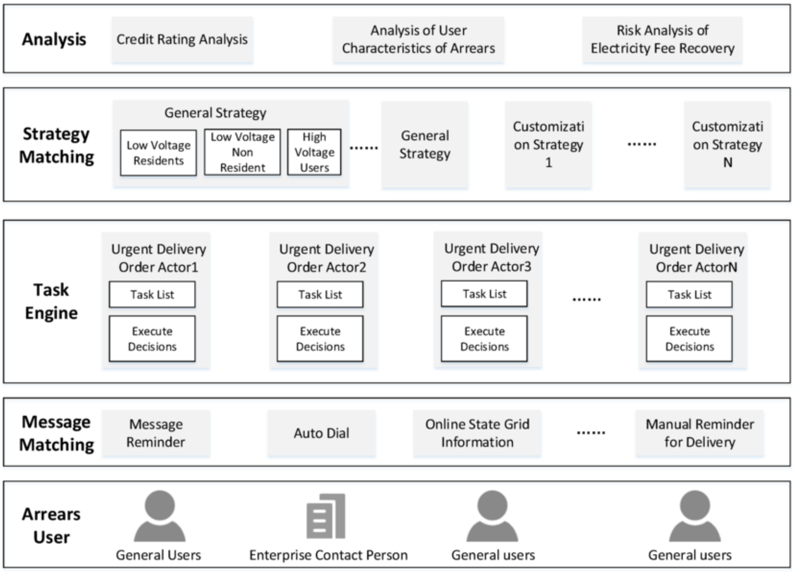

Figure 1. Overall Business Architecture

Marketing 2.0 generates accounting arrears and real-time balance information based on user types, monthly issuance status, and cost control calculations, and implements a step-by-step reminder application according to the reminder strategy. The reminder information is sent to customers according to the message strategy set by the user, and all reminder information is processed into work orders. The overall main business process is as follows:

(1) Reminder strategy matching: After the monthly issuance work is completed or the cost control day calculation is completed, the reminder strategy will automatically match the work. Users who meet the matching conditions will automatically generate reminder work orders. At the same time, customer managers can manually add reminder task orders.

(2) After the reminder task work order is generated, message strategy matching is carried out based on the reminder user information, and first level reminder work is carried out according to the matching results.

(3) After 24 hours of the first level reminder work, check the payment information of the user in the reminder task work order. If payment is not made within 24 hours, the second level reminder work will be triggered.

(4) When triggering the second level reminder work, synchronously adjust the customer credit rating level and downgrade it by one level according to the current level.

(5) After 24 hours of the second level reminder work, check the payment information of the user in the reminder task work order. If payment is not made within 24 hours, the third level reminder work will be triggered.

(6) After triggering the three-level reminder work, the current user will be included in the list of users to be verified, and the customer's current credit rating will be lowered by one level synchronously.

(7) After 24 hours of the third level reminder work, check the payment information of the user in the reminder task work order. If the payment is not made within 24 hours, the current reminder task work order will be set as "incomplete", and this information will be reminded and notified in real-time monitoring data and the power supply station reminder application.

(8) For reminder tasks in the "incomplete" status, check the user's payment information in the reminder task ticket every 24 hours. If the customer pays, the ticket status will change. If the customer still fails to pay before the end of the month, the ticket will be set as "reminder failed".

2.2. Analysis of Customer Credit Rating Levels

Firstly, data preprocessing is carried out to deal with missing and abnormal values in historical payment data. Then, useful features such as payment amount, payment frequency, and overdue times are extracted from the payment data. Finally, the features are standardized. Then, the preprocessed data is clustered using the K-means clustering algorithm. The standardized data is used as the sample data, and the elbow method can be used to determine the k value. The k points are clustered around each center, and the k-means algorithm is used to calculate the distance to each center. The sample is then classified into the class with the shortest distance to the center. After clustering, the center point positions of each cluster are recalculated until the positions of the k center points remain unchanged, and finally divided into 4 levels. Based on the clustering results, compare and analyze the users in each group to determine the credit rating of power users. For example:

A-level: No theft or illegal use of electricity within three years, timely settlement of electricity bills, monthly settlement of electricity bills within one year, and even the ability to pay electricity bills in advance.

B-level: There has been no electricity theft or illegal use within three years, and as of last month, there has been no accumulated arrears of electricity bills. However, there have been instances of electricity bill arrears within a year, but timely payment can be made through telephone collection.

C-level: No electricity theft or illegal use within three years, but accumulated overdue electricity bills for more than one month as of last month.

D level (or serious breach of trust level): Has engaged in electricity theft or illegal electricity use within three years, or has accumulated overdue electricity bills for more than two months as of last month.

Furthermore, customer credit indicator features can be used as input variables, customer credit labels as target variables, and an electricity customer credit rating model can be constructed based on LSTM+XGBoost algorithm to predict credit evaluation levels. XGBoost parameters can be optimized through cross validation and grid search.

2.3. Analysis of User Characteristics of Arrears

For different user groups and overdue and credit situations, provide information on overdue users such as remaining days, user identity, information loss, users who have failed multiple deductions, and users who have repeatedly urged for payment. Specifically, as follows:

(1) Remaining days analysis: Based on the user's historical electricity usage, estimate the remaining days of electricity consumption for the current month.

(2) User identity analysis: Based on service trace records, timely confirm and update user identity, and determine whether there is a change in payment subject for the current user, such as transfer of ownership, change in value-added tax invoicing information, etc., which may lead to a change in the customer's payment subject.

(3) Information loss analysis: Based on service traces and reminder records, analyze customer loss situations and mark potential lost users.

(4) Multiple Withholding Failure User Analysis: Based on the user ID and withholding failure situation, query users who have received more than the specified number of channel withholdings per month (default 10).

(5) Multiple reminder user analysis: Based on user ID and SMS sending status, query users who receive more than a specified number of reminder messages per month (default 10).

(6) Analysis of High Voltage Users at Risk of Arrears: Based on user ID and payment time statistics, query high voltage users who have paid their overdue accounts after the specified date each month or have exceeded the deadline for multiple consecutive months (0:00 on the specified date each month);

(7) Analysis of Complaint Risk and Sensitive Users: Based on user ID and sensitive user tags, query users with complaint risk and sensitive users on a monthly basis.

(8) User analysis of government funding units: Based on user ID and issuance time, query monthly electricity bills of government funding unit users;

(9) Analysis of Regular Payment Users: Based on user ID and payment time, query monthly regular payment users. For example, Zhang San receives his salary on the 15th of each month and pays his electricity bill on the 15th of each month;

(10) Multiple manual on-site user analysis: Based on the user ID and manual on-site situation, query the information of users whose monthly manual on-site work orders exceed the specified number.

(11) No need to remind users for fee analysis: Based on user ID and payment time statistics, users who have paid their outstanding accounts before the 16th of each month and those who have long-term deposits or successful deductions are considered high-quality customers; Add prompts to the approval user process.

(12) Post paid user analysis: Based on the user ID and release time, query the monthly electricity bills of users who have paid and successfully subscribed.

For long-term overdue users, measures such as door-to-door collection and legal litigation can be taken; For occasional users who owe fees, they can be reminded to pay in a timely manner through SMS, phone calls, and other means; For users who often forget to pay, more frequent reminders can be set up; For users with poor credit records, stricter reminder measures should be taken. At the same time, through on-site visits, user feedback, and other methods, complete customer on-site electricity usage information, collect user opinions and suggestions on electricity payment services, and continuously improve and optimize services. Analysis of overdue users helps to more accurately assess the risk level of electricity bill recovery and develop more effective risk management measures.

2.4. Risk Analysis of Electricity Fee Recovery

Firstly, collect bank data, electricity data, and network crawling data: customers' loan records, repayment history, credit scores, users' electricity consumption, payment history, arrears records, GDP data, industry development indices, and macroeconomic indicators. Then, fill in or delete missing data, normalize numerical data, and convert categorical variables such as credit rating and industry category into numerical variables. Based on business knowledge and data correlation analysis, select features that have an impact on the risk of electricity bill recovery. Next, based on the preprocessed data, a three-layer structure is established, which is divided into a target layer (electricity bill recovery risk), a criterion layer (arrears situation, credit status, macroeconomic status, industry development status, etc.), and an indicator layer (arrears amount, arrears frequency, credit score, GDP growth rate, industry growth rate, etc.). Construct pairwise comparison judgment matrices for the standard layer and indicator layer, use the 1-9 scale method to represent relative importance, and calculate the eigenvectors and maximum eigenvalues of each judgment matrix for consistency testing to ensure the rationality of the judgment matrix. Combine the weights of each criterion layer and indicator layer to obtain the final feature weights.

Finally, the preprocessed data is used as the training set, and the risk of electricity bill recovery (such as whether or not there are outstanding fees, the amount of outstanding fees, etc.) is taken as the target variable. The random forest algorithm is used to train the model and obtain a preliminary risk prediction model. The prediction results of the random forest model are processed using the entropy method, and the information entropy and weight of each feature are calculated to further verify the results of the Analytic Hierarchy Process (AHP). Combine the feature weights of AHP and the predictive ability of random forests to fuse and optimize the model. Consider using the feature weights determined by AHP and entropy method as input layer weights or regularization terms for the neural network, and automatically adjusting the hyperparameters of the neural network through Bayesian optimization to improve the model's generalization ability. Train the model using the training set and evaluate its performance on the validation set through cross validation. Conduct a risk assessment of electricity fee recovery for new or existing users, set risk levels based on the assessment results, and provide warning and management. The risk level of user arrears can be divided into five risk levels, as follows.

(1) First level high-risk users are at risk of being unable to pay their electricity bills, and there is a need to increase the intensity of reminders, intervene and report in advance, and form a list of users to be supervised.

(2) Second level medium to high-risk users, who have a history of frequently owing electricity bills. In addition to increasing efforts to urge payment, they also negotiate with customers to adjust payment methods (such as withholding).

(3) Third level medium risk users who may face financial risks due to policies, industry, or personal reasons should prioritize electricity payment reminders and be included in real-time reminders.

(4) Level 4 low-risk users with insufficient real-time balance and outstanding electricity bills for more than 10 working days after issuance (with no historical arrears or habit of paying at the end of the month) pose certain risks. In combination with intelligent fee collection strategies, we will carry out fee collection.

(5) Level 5 risk-free user, who is a regular electricity user and has no history of overdue payments.

2.5. Channels for Reminder Information

Maintain and update user payment reminder channels, including but not limited to SMS, WeChat, phone, door-to-door, online State Grid, Dianebao, etc; It is necessary to control all marketing SMS and query all SMS sent by users through Marketing 2.0. When the business personnel use it, the 95598 number is displayed for outbound calls, and the control of reminder channels should be strengthened.

3. Design of Payment Reminder Strategy

3.1. General Fee Collection Strategy

A. Low voltage resident/non resident reminder strategy

(1) Based on the 95598 work order and user payment habits, for users who are sensitive to payment reminders and have good payment habits, with the help of tags, if these users fail to pay after a fixed date (such as the 15th) every month, the customer manager will manually send a reminder SMS.

(2) Users will be reminded of fees based on a customized fixed amount (if the fixed amount is less than or equal to 0, the reminder will be made when the fixed amount is reached), and the reminder method is optional.

(3) Remind users of fees based on custom days. (After the user owes the fee, set an offset value of n. If the offset value is not paid after n days, the payment will be reminded.) The reminder method is optional.

(If SMS is selected as the above payment reminder method, an offset value of m can be set. If payment is still not made after m days, the system will initiate an intelligent outbound call. The intelligent outbound call can set an offset value of m. If payment is still not made after m days, the customer manager will manually come to the customer's door to remind them.).

(4) With the help of tags, for users who have repeatedly urged for payment but still refuse to pay, and are only willing to pay when there is a power outage, the customer manager will initiate the power outage process based on the actual situation, without using the system to urge payment.

B. High voltage user reminder strategy

(1) Remind users of fees based on custom days. (Set an offset value of n after the user owes the electricity fee. Considering that the electricity fee for high-voltage users may be too high, if the user has paid n% of the outstanding electricity fee after n days of the offset value, the next round of collection will not be carried out. If the user still fails to pay after n days of offset, collection will be carried out again.) The collection method is optional.

(If SMS is selected as the above payment reminder method, an offset value of m can be set. If payment is still not made after m days, the system will initiate an intelligent outbound call. The intelligent outbound call can set an offset value of m. If payment is still not made after m days, the customer manager will manually come to the customer's door to remind them.).

(2) For users who refuse to pay despite multiple reminders and are only willing to pay due to power outages, the customer manager will initiate the power outage process based on the actual situation, without using the system to urge payment.

3.2. Customized Payment Reminder Strategy

A. Withholding failed user

Group characteristics: postpaid withholding users, 1.0 existing fee control withholding users

Reminder strategy: Send a text message (Level 1 reminder) within X days after 3 failed deductions in the current month. If the electricity bill is not paid within 24 hours, transfer the call to an external call (second level reminder); If the phone call is not answered after 3 outbound calls, or if the electricity bill is not settled after 24 hours of 3 outbound calls, a reminder will be sent to the transfer person to urge payment (Level 3 reminder).

Business Support: SMS Reminder for Withholding Failure. After multiple consecutive months (default 3 months, adjustable) of withholding failure, the reminder for the withholding agreement will be canceled.

B. Multiple reminders from users

Group characteristics: Users who receive more than 10 reminder messages per month.

Reminder strategy: SMS alerts are added to the standard reminder frequency of each unit, and after 2 additional reminders, users are reminded to pay through intelligent outbound calls, phone calls, and other methods (second level reminder). If the electricity bill is not settled within 24 hours after the last additional reminder, it will be transferred to the list of users to be verified and a power outage work order will be generated (Level 3 reminder).

Business support: Regularly extract the SMS sending status of the previous month every month and update records for users with more than 10 messages.

C. High voltage users at risk of overdue fees

Group characteristics: High voltage users at risk of arrears

Reminder strategy: Within N days after the issuance of electricity bills, automatic SMS notifications will be sent to the accounting contacts of high-voltage users who are at risk of arrears (second level reminder). If electricity bills are not paid within 48 hours, they will be automatically transferred to the customer manager for manual reminder after 12 days (third level reminder).

Business support: High voltage users with a risk analysis level of intermediate or above for electricity fee recovery.

D. Risk of complaints and sensitive users

Group characteristics: Possessing complaint risks and sensitive users

Reminder strategy: Within N days after the issuance of electricity bills, automatic SMS notifications will be sent to the accounting contacts of high-voltage users who are at risk of arrears (first level reminder). If electricity bills are not paid within 48 hours, external calls will be made (second level reminder); If the phone call is not answered after 3 outbound calls, or if the electricity bill is not settled after 24 hours of 3 outbound calls, it will be automatically transferred to the customer manager for manual collection and reminder (Level 3 collection).

Business support: Possess complaint risks and sensitive users

E. Users with too many phone calls

Group characteristics: Users with more than 3 telephone work orders per month.

Delivery reminder strategy: Remind users to pay through intelligent outbound calls, phone calls, and other methods (second level reminder). If the last additional reminder does not settle the electricity bill within 24 hours, it will be transferred to the customer manager for manual payment reminder (third level reminder).

Business support: Regularly select users with excessive phone calls for electricity consultation, opinions, and complaints on a monthly basis.

F. Intelligent payment reminder for group households

Group characteristics: Users set as group households by the system

Expediting strategy: N days after the electricity charge is issued (settable), the group user detailed bill will be automatically generated and sent to the online state network or WeChat official account, and detailed data display is supported.

Business support: Every month, the account manager needs to confirm whether the accounting contact person and contact information of the group account have been updated.

G. Government funding units

Group characteristics: Government funding units

Reminder strategy: Within N days after the issuance of electricity bills, an automatic SMS notification will be sent to the accounting contact person (Level 1) of the government funding unit. If the electricity bill is not paid within 48 hours, it will be transferred to an outbound call (Level 2); If the phone call is not answered after 3 outbound calls, or if the electricity bill is not settled after 24 hours of 3 outbound calls, it will be automatically transferred to the customer manager for manual collection and reminder (Level 3). Automatically generate detailed user bills of government appropriation units, send them to the online state network or WeChat official account, and support detailed data display.

Business support: Mark government funding units.

H. Regular payment users

Group characteristics: timed payment users

Delivery reminder strategy: This type of user limits the number of reminders, and does not send reminder messages before the scheduled period (not exceeding the 18th). After the scheduled period, they will notify the other party through text messages.

Business support: timed payment users

4. Conclusion

The artificial intelligence based electricity payment reminder and control system and method proposed in this article follow the core concept of "more reminders, less stops", expand reminder channels, reduce reminder costs, and deeply develop and implement a series of precise and effective intelligent reminder strategies to ensure timely collection of electricity bills. By improving the efficiency of delivery reminders and reducing them, we can solve the problem of urgent delivery for important and livelihood customers, enhance customer satisfaction and loyalty, inject new vitality into the sustainable development of power enterprises, and build a more harmonious and win-win power supply and consumption relationship.

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Confirming the Structural Validity and Perceptual Patterns of Employment Success Factors Among Engineering Graduates from Vocational College in China: A CFA and MDS Approach

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Abstract. The employment situation of vocational college students majoring in engineering in China is currently receiving increasing attention. This study aims to verify the core factors influencing the successful employment of such students and visualize the perceived relationships among these factors. Based on the Social Cognitive Career Theory (SCCT), this study employs Confirmatory Factor Analysis (CFA) to verify the structural validity of ten latent factors. Subsequently, the multidimensional scaling method (MDS) was used to reveal the clear perceived clustering and relationship distances among the constructs. These findings provide theoretical and practical insights for vocational education, personal planning, and policy design in the field of vocational education.

Keywords. Successful employment, engineering graduates from vocational college, Social Cognitive Career Theory

1. Introduction

With the continuous expansion of higher education in China, the number of engineering graduates from higher vocational colleges has been increasing year by year, while their employment situation has become increasingly challenging [1]. According to data from the Ministry of Education, the number of college graduates nationwide reached 11.79 million in 2024 and is expected to exceed 12.20 million in 2025, setting a new record. The rising number of graduates has led engineering-focused vocational colleges to face common issues such as "difficulty in finding employment," "job-position mismatch," and "slow employment progress." Studies indicate that the professional matching employment rate for engineering graduates from vocational colleges has remained between 50% and 60%, with the proportion of "slow employment" exceeding 40% in some regions [2][3]. These challenges not only affect the individual development of

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students but also pose critical issues for the teaching models, institutional mechanisms, and quality assurance systems of vocational education. In countries like Germany and the United States, vocational education systems have shown positive employment outcomes due to strong support mechanisms and alignment with industry needs [4][5].

To alleviate employment pressure and address structural imbalances, the Chinese government has introduced a series of reform policies, such as the National Vocational Education Reform Implementation Plan, the 13th Five-Year Plan for Vocational Education Development, and the "1+X" certificate system. These policies emphasize deep collaboration between schools and enterprises, the enhancement of students' practical skills, and the improvement of societal recognition of vocational education [6]. Engineering graduates from vocational colleges are increasingly regarded as key human resources for industrial upgrading and technological innovation. However, the implementation of these policies still faces "last mile" challenges, including outdated curricula, weak career planning education, and unclear pathways for industry-education integration [7].

At the same time, the labor market is undergoing profound transformations. On one hand, technological advancement has raised the skill requirements for engineering talent; on the other hand, graduates' employment values and career preferences are also evolving [8]. Under such circumstances, the employment rate alone is no longer sufficient to fully reflect the quality of employment. It is necessary to understand the employment structure and psychological characteristics of high-quality engineering graduates from multiple dimensions, explore the underlying cognitive patterns, and promote personalized guidance and targeted policy interventions.

Although prior research has explored career choices, job matching, and skill development among vocational college graduates, it often lacks rigorous structural validation of the factors influencing successful employment. Additionally, few studies have examined how students perceive and prioritize these factors using advanced analytical methods. To address these gaps, this study focuses on engineering graduates from Chinese vocational colleges, aiming to (1) validate the structural dimensions of employment success factors through confirmatory factor analysis (CFA), and (2) map students' perceptual patterns using multidimensional scaling (MDS) analysis.

2. Literature Review

2.1. Related Concepts

Successful employment is commonly defined as achieving career goals through preparation, goal-setting, and active labor market participation, involving both a sense of accomplishment and a self-regulated career management process [9][10][11].

Social Cognitive Career Theory (SCCT) addresses this gap by emphasizing the interaction of individual, social, and environmental factors, especially through constructs like self-efficacy, outcome expectations, and career goals [12]. The Career Self-Management Model within SCCT, developed by Lent and Brown (2013), further incorporates career actions and social support, highlighting how cognitive and contextual variables jointly shape employment outcomes [13].

Confirmatory Factor Analysis (CFA), a structural equation modeling method, is widely used to validate latent constructs like self-efficacy and employability in career research, ensuring the reliability of theoretical models [14]. MDS, as an exploratory tool, visually maps perceived similarities among career-related factors, helping to reveal students' cognitive patterns and decision-making processes [15][16].

2.2. Foreign Literature Review

International studies have examined vocational graduates' employment outcomes under varied education systems. For example, Germany's dual-track model links closely to high employment and industry ties [4], while research in the United States emphasizes the role of community colleges and individualized career services [5]. These comparisons underscore the importance of context-sensitive career models.

Scholars in foreign academic settings have conducted extensive empirical research within the SCCT framework regarding career choices and employment behaviors. For example, Lent et al. (2008, 2010, 2011) employed path analysis to examine the relationships among career interests, self-efficacy, and employment decisions, revealing that career goals serve as a mediating factor in career choice processes [17][18][19]. Building on this foundation, Lent et al. (2021) extended SCCT to analyze predictors of job satisfaction and retention, offering broader insight into work-related outcomes [20]. Byars-Winston et al. (2010) found that self-efficacy and social support significantly influence career decisions across different academic backgrounds, including STEM and non-STEM fields [21]. Shin et al. (2021) confirmed the positive impact of social support on Korean students' career decision-making self-efficacy [22]. In addition, Hirschi (2018) and others have applied SCCT to career planning in uncertain environments, underscoring the importance of adaptability [23].

2.3. Research Review

In summary, prior studies on vocational college graduates have examined factors such as professional skills, career planning, and school–enterprise cooperation, contributing to our understanding of employment outcomes in technical and vocational education. Despite valuable contributions, several notable gaps persist in the current literature, particularly regarding structural validation, students' cognitive perceptions of employment success, and the integration of analytical methods:

- Limited structural validation – Most studies use descriptive or regression analyses, with few applying CFA to test the factor structure of employment success among vocational engineering students.
- Neglect of student perceptions – Research rarely addresses how students cognitively perceive or prioritize employment-related factors, and the use of MDS remains scarce.
- Lack of integrated analysis – Structural validation and perceptual mapping are seldom combined, leading to a fragmented understanding of employability.

To address these gaps, this study applies CFA to validate the structural model of employment success factors and uses MDS to explore students' perceptual patterns. By integrating these methods, the study provides a dual perspective on how key factors influence employment outcomes, offering insights for vocational education reform and career guidance.

3. Methodology

3.1. Research Design

This study aims to explore the key factors influencing successful employment among engineering graduates from vocational colleges in China, drawing on the Career Self-Management Model within the SCCT. The SCCT framework–which emphasizes the interaction among personal attributes, contextual influences, and self-regulatory behaviors–provides the theoretical foundation for both the selection of variables and the design of the questionnaire.

A quantitative research approach was adopted, with data collected via the online platform WJX.com. To ensure data uniqueness, participants were required to submit their phone numbers, which were encrypted, securely stored, and deleted after analysis to protect personal privacy.

Guided by the self-management model of SCCT, the questionnaire captured multiple domains theorized to affect employment outcomes, including person input and background, learning experiences, self-efficacy, outcome expectations, personality traits, social support and barriers, career goals, and career actions (see Figure 1).

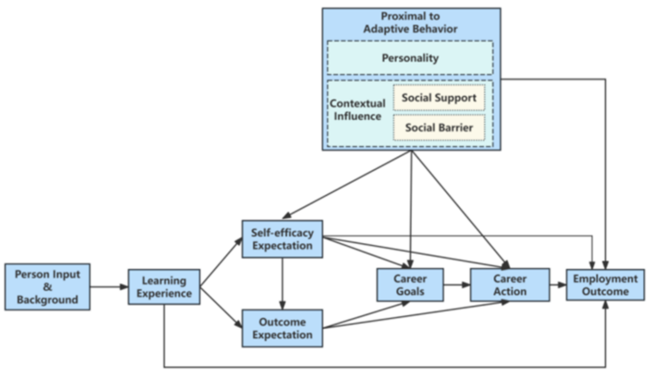

Figure 1. Career Self-Management Model. Source: Lent et al. (2013)

In designing the questionnaire, this study adhered to the principle of conciseness and efficiency, prioritizing validated and streamlined scales to ensure reliability, validity, and completion rates. The questionnaire consists of two sections: the first section collects demographic information, including gender, place of origin (urban or rural), family location, household income, education level of father and mother, and whether it is a "Double High Project" institution. The second section measures core variables using well-established scales, including the Career Exploration and Decision-Making Learning Experience Scale (Chinese version, 2019), Jinde's Ten-Item Big Five Personality Inventory (2013), General Self-Efficacy Scale (Chinese version, 2001), Career Decision Outcome Expectations Scale (Yu, 2004), Career Influence Inventory (Fisher, 1999), Career Goal Scale (Yu, 2004) [24], and Career Exploration Scale (Blau, 1993) [25]. The original Likert scaling was retained, where the Career Exploration and Decision-Making Learning Experience Scale and the Career Exploration Scale use a 5-point Likert scale, the Big Five Personality Inventory employs a 7-point Likert scale, and all other scales adopt a 4-point Likert scale.

3.2. Sample

Data were collected via Wenjuanxing from 2023 graduates of three vocational colleges in Guangdong (East), Sichuan (West), and Hunan (Central). A stratified purposive sampling method was used to ensure diversity in geographic region and institutional level, covering one "Double High Project" institution and two ordinary institutions.

The sample size was determined based on the questionnaire’s 72 items, following the 5:1 ratio guideline for structural equation modeling, ensuring sufficient power for confirmatory factor analysis.

Within each college, participants were drawn from key engineering majors. Graduate advisors assisted in distributing the questionnaire to final-year students. A total of 503 responses were collected; after excluding 19 invalid cases, 484 valid responses remained.

3.3. Statistical Analysis

Data analysis in this study was conducted using SPSS 26.0 and AMOS 24.0. Descriptive statistics were performed in SPSS 26.0 to examine the demographic characteristics of the respondents and the distribution of key variables. Given that the SCCT provides a mature and widely validated theoretical framework, and considering that Zhao (2023) [26] has already applied both exploratory and confirmatory analyses to Chinese undergraduate populations using the same model structure, this study did not place emphasis on conducting an exploratory factor analysis (EFA). Instead, CFA was carried out in AMOS 24.0 to assess the structural validity of the measurement model. Additionally, MDS was applied to explore the perceptual patterns of employment success factors. CFA was used to confirm the validity of the constructs derived from SCCT, while MDS helped reveal the underlying perceptual structure among factors influencing employment success outcomes.

4. Research Findings

4.1. Descriptive Statistical Analysis

Table 1 summarizes the demographics of the 484 respondents. Females made up 57.64%, and 42.36% were male. Urban students accounted for 57.64%, while 42.36% came from rural areas.

Regionally, 49.79% were from Eastern China, 29.34% from the West, and 20.87% from Central China. Most came from low (40.50%) or middle-low (38.02%) income families, with only 20.06% from middle-high and 0.83% from high-income households. Parental education was generally low: over 61% of fathers and 63% of mothers had only junior high school or below; less than 3% held a master’s degree or above. Most students (80.99%) were from ordinary higher vocational colleges, with 19.01% attending Double First-Class institutions.

Table 1. Person input and background of respondents

Variable	Category	Sample Size	Percentage (%)
Gender	Male	205	42.36
	Female	279	57.64
Rural/Urban	Rural	205	42.36
	Urban	279	57.64
Family Location	Eastern	241	49.79
	Central	101	20.87
	Western	142	29.34
Household Income Level	Low Income	196	40.50
	Middle-Low Income	184	38.02
	Middle-High Income	100	20.06
	High Income	4	0.83
Father's Education Level	Junior High or Below	297	61.36
	High School or Technical Secondary School	130	26.06
	Diploma or Bachelor's Degree	44	9.09
	Master's Degree or Above	13	2.69
Mother's Education Level	Junior High or Below	307	63.43
	High School or Technical Secondary School	125	25.83
	Diploma or Bachelor's Degree	37	7.64
	Master's Degree or Above	15	3.1
Institution Type	Double High Project Vocational College	92	19.01
	Ordinary Higher Vocational College	392	80.99

Reliability analysis showed strong internal consistency, with Cronbach's α values ranging from 0.872 to 0.908 for individual constructs. The overall α was 0.901, and the standardized α reached 0.928—both well above the 0.700 threshold, indicating good reliability.

Prior to CFA, an EFA using principal axis factoring and Promax rotation was performed to explore the underlying factor structure. The Kaiser-Meyer-Olkin (KMO) value was 0.857, and Bartlett's Test of Sphericity was significant (χ^2 = 13767.79, df = 4371, $p < 0.001$), indicating adequate sampling and inter-item correlations. Items with low factor loadings (< 0.40) or high cross-loadings were removed. The resulting structure aligned well with the SCCT self-management model, supporting the decision to proceed with CFA. Ten latent factors were identified: Learning Experience (LE), Personality (PL), Self-efficacy Expectation (SE), Outcome Expectation (OE), Socail Support from teachers (SST), Social Support from family (SSF), Social Support from friends (SSFR), Social Barriers (SB), Career Goals (CG), and Career Actions (CA).

4.2. Confirming the Structural Validity of Employment Success Factors

This section uses CFA to evaluate the SCCT self-management model for Chinese engineering diploma graduates. The model included 10 latent factors and 72 observed items, based on 484 valid responses. Although the commonly recommended N:p ratio for confirmatory factor analysis is 10:1, several methodological studies suggest that ratios as low as 5:1 can still yield reliable results when the model is well specified, factor loadings are moderate to high, and the sample exceeds 300 cases [27][28]. In the subsequent study, all key model fit indices fall within acceptable ranges, indicating that the parameter estimates remain reliable and the structural model is robust.

Items with factor loadings below 0.50–such as LE2, PL4, SE2, SSF4, and SSFR8–were removed to improve model fit [29]. All ten factors showed strong composite reliability (CR > 0.80) and acceptable AVE values. According to Fornell and Larcker (1981), AVE slightly below 0.50 is acceptable if CR > 0.60 [30]. This confirms the model's reliability and convergent validity [31].

As shown in Table 2, model fit indices were strong: $\chi^2/df = 1.261$, RMSEA = 0.023, RMR = 0.033, and SRMR = 0.040. Incremental indices (CFI, NNFI, IFI, TLI) all exceeded 0.90. Though GFI (0.858) and NFI (0.880) were slightly below ideal, they remained acceptable given model complexity.

Table 2. Model Fitness Index (Items:72)

Commonly Used Indicators	Cardinality Ratio of Freedom $\chi2/df$	RMSEA	RMR	GFI	CFI	NFI	NNFI	IFI	TLI	SRMR
Judgment Criteria	<3	<0.10	<0.05	>0.9	>0.9	>0.9	>0.9	>0.9	>0.9	<0.1
Value	1.261	0.023	0.033	0.858	0.910	0.880	0.906	0.911	0.906	0.040
Default Model: $\chi2(2556)=9624.237$, $p<0.001$										

To further refine the model, the study incorporated modification index (MI) analysis. While there is no absolute threshold, MI values above 20 typically indicate potential misspecifications or strong cross-loadings. For instance, CA2 showed high MI values with both LE and SB, suggesting conceptual overlap; SE1 and SSFR6 also exhibited cross-loading tendencies. As a result, three items–CA2, SE1 and SSFR6–were removed. SE1 reflected general optimism rather than task-specific self-efficacy; CA2 involved passive information registration rather than active career behavior; SSFR6, although career-related, was phrased too broadly to capture specific peer support.

Their removal improved model fit (see Table 4) without compromising theoretical integrity. Compared to Table 3, Table 4 shows slight improvements in key fit indices such as CFI, NNFI, and IFI, indicating a modest enhancement in model fit after the removal of four low-loading items. Given the large number of observed variables and latent constructs, some global fit indices remained slightly below optimal thresholds. Further model refinement–such as item reduction or higher-order factor modeling–may help enhance parsimony and improve overall fit in future studies.

Table 3. Factors and Measurement Items - MI Index

Measurement Item	Relationship	Factor	MI Value	Par Change
CA2	Measurement	LE	20.653	-0.198
CA2	Measurement	SB	22.546	-0.116
SE1	Measurement	LE	24.155	-0.16
SE1	Measurement	OE	22.272	0.091
SE1	Measurement	CG	21.988	0.089
SSFR6	Measurement	LE	46.669	0.138
SSFR6	Measurement	SE	23.517	0.093
SSFR6	Measurement	SST	21.346	-0.226

Table 4. Model Fitness Index (Items:69)

Commonly Used Indicators	Cardinality Ratio of Freedom $\chi2/df$	RMSEA	RMR	GFI	CFI	NFI	NNFI	IFI	TLI	SRMR
Judgment Criteria	<3	<0.10	<0.05	>0.9	>0.9	>0.9	>0.9	>0.9	>0.9	<0.1
Value	1.267	0.024	0.033	0.863	0.912	0.898	0.908	0.914	0.908	0.040
Default Model: $\chi2(2346)=9131.625$, $p<0.001$										

According to Hair et al. (2019), an HTMT value below 0.85 indicates acceptable discriminant validity in structural equation modeling [32]. In this study, all HTMT values met this criterion, suggesting clear distinction among the ten latent constructs. Additionally, the square root of each construct's AVE exceeded its correlations with other constructs, further supporting strong discriminant validity. These results confirm that the model structure is sufficiently distinct, and a second-order factor analysis is not required.

4.3. Visualizing the Perceptual Patterns of Employment Success Factors

The CFA identified key factors influencing employment success among engineering graduates from Chinese vocational colleges. To further examine their relationships, MDS analysis was conducted.

To construct the dissimilarity matrix, squared Euclidean distance between the ten latent constructs was used. This method captures the conceptual spacing between factors based on perceived differences in their influence on employment success. The matrix was analyzed using the PROXSCAL algorithm in SPSS 26, ensuring high transparency and replicability in the analysis.

MDS visualizes factor relationships by mapping dissimilarities in a two-dimensional space [33]. Based on the survey, ten factors (LE, PL, SE, OE, SST, SSF, SSFR, SB, CG, CA) were included. A 10×10 dissimilarity matrix was created using Euclidean distance, summarizing the perceived differences between factor pairs.

Using SPSS 26, MDS analysis showed a stress value of 0.011, indicating excellent model fit. The RSQ value reached 0.99965, suggesting that the two-dimensional solution accurately represents the original data structure. These results confirm the MDS model's effectiveness in capturing perceptual patterns among employment-related factors.

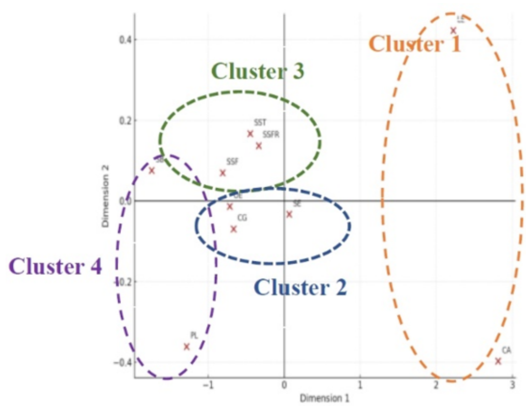

Figure 2. Derived Stimulus Configuration Euclidean Distance Model

Figure 2 shows the MDS results based on the final dissimilarity matrix. In the two-dimensional space, the relative distances between the ten factors reflect their conceptual similarities in the context of successful employment. Closer factors tend to share similar roles within the SCCT framework, revealing how cognitive, behavioral, and contextual elements interact.

Based on spatial proximity and quadrant distribution, the ten factors were grouped into four perceptual clusters. Cluster 1 (LE, CA) is located in the first quadrant, far from the origin, indicating these outcome-related behaviors reflect the end results of upstream influences. Cluster 2 (SE, OE, CG) appears centralized and cohesive, aligning with SCCT's emphasis on these cognitive-personal factors as drivers of career goals.

Cluster 3 (SST, SSF, SSFR) is compact and near the origin, highlighting their role as core social support systems enhancing self-efficacy. Cluster 4 (PL, SB) represents contextual constraints that may hinder employment by lowering perceived efficacy. Overall, the four-cluster structure illustrates the multidimensional interplay among personal, social, and contextual variables.

5. Conclusions and Recommendations

This study, based on CFA and MDS analysis, identified ten significant factors influencing the successful employment of engineering graduates from vocational colleges in China: LE, PL, SE, OE, SST, SSF, SSFR, SB, CG, and CA. Through CFA, this study established the good structural validity of these ten latent variables. Subsequently, using MDS, the perception structure and spatial relationship among these factors were further revealed.

Based on the findings, the following recommendations are proposed at the levels of government, vocational colleges/enterprises, and individuals to improve the employment quality of engineering graduates:

- Government level: Enhance employment guidance and strengthen practice-oriented preparation. Since learning experience and social support significantly influence employment success, the government should invest more in career services and promote preparatory courses and internships in vocational colleges. Local authorities are encouraged to cooperate with institutions to implement "campus-to-position" programs, especially targeting students from rural or under-resourced backgrounds, providing tailored consultation and support.
- Vocational college and enterprise level: Improve cooperative education and social support mechanisms. As teacher's social support proved crucial, vocational colleges should train instructors in career guidance and build a mentor-student employment support system. Enterprises should offer internships and real project opportunities to support students' career actions with meaningful experiences, while also creating fair evaluation systems to reduce social barriers and boost graduates' confidence and belonging.
- Individual level: Strengthen self-efficacy, set clear goals, and take consistent action. As outcome expectations and goals are closely linked, students should affirm their strengths, set realistic yet challenging goals, and engage in continuous preparation (e.g., training, resume polishing, mock interviews). They should also actively seek emotional and informational support from teachers, family, and peers to better navigate career challenges.

6. Research Shortcomings and Future Prospects

This study used CFA and MDS to identify key factors influencing the employment success of engineering graduates from Chinese vocational colleges, analyzing both structural and perceptual dimensions. However, the use of cross-sectional data limits insights into causal relationships and dynamic changes; future studies could adopt longitudinal or experimental designs to address this.

The sample was regionally limited, which may affect the generalizability of the findings. Expanding the sample to more provinces and institutional levels would enhance representativeness.

Finally, while the MDS map illustrates overall perceptions, it does not fully explore group differences. Future research could incorporate cluster analysis or structural equation modeling to examine how students from different backgrounds perceive employment factors and how this affects outcomes.

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Application and Effectiveness Analysis of a Prescription Dispensing Virtual Simulation Teaching System in Pharmacology Education

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Abstract. Objective: To explore the impact of virtual simulation prescription dispensing teaching system in pharmacology theoretical education on students' final academic performance. **Methods:** A total of 112 students from Class 1 and Class 2 (2023 cohort) of the Pharmaceutical Equipment Application Technology program were randomly assigned to a control group (Class 1, n = 56) and an experimental group (Class 2, n =56). Experimental Group students were permitted unrestricted access to prescription dispensing virtual simulation system for post-class practice, completing 2-hour instructor-supervised practice sessions and online assessments at midterm and final semesters; control group counterparts adhered to conventional methods (4-hour sessions: oral instruction on key concepts, Q&A sessions, and paper-based testing. All other teaching content, methods, and classroom management were standardized and delivered by the same instructor. At the end of the semester, SPSS 26 was used to analyze the final pharmacology exam scores. **Results**: The experimental group demonstrated significantly superior final examination performance compared to controls (81.46 ± 7.18 vs. 75.89 ± 6.91, $P < 0.01$). Additionally, the experimental group's final scores were significantly correlated with their virtual simulation performance. **Conclusion:** Application of prescription dispensing virtual simulation systems in pharmacology education may enhances final exam performance through improved engagement and real-time feedback mechanisms.

Keywords. Prescription dispensing; Virtual simulation; Pharmacology; Effectiveness analysis

1. Introduction

Virtual simulation refers to a technology that utilizes computer systems to simulate real-world environments, systems, or processes. Originating in the 1940s–1950s from advancements in computational and mathematical modeling, it was initially applied in aerospace and military domains but has since expanded to diverse fields such as industrial

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medical education [1], virtual simulation is emerging as a core driver of pedagogical innovation. In pharmacology teaching, applications such as PK-Sim models (simulating drug absorption, distribution, metabolism, and excretion, or ADME), pharmacodynamics (PD) simulations, virtual organ-on-a-chip systems, virtual drug interaction analyses, virtual cytotoxicity testing, virtual pharmacy systems, virtual clinical scenarios, case-based precision medication simulations, and antibiotic sensitivity testing are revolutionizing traditional approaches to drug mechanism instruction and skills training. By enabling molecular-level interactions, dynamic process visualization, and risk-free experimental design, virtual simulation shifts pharmacology education from static textbook memorization to immersive three-dimensional exploration.

The application of virtual simulation teaching systems has been demonstrated to significantly enhance students' learning motivation and technical competency development [2-3], particularly in pharmacological animal experimentation where such computer-based platforms virtually eliminate ethical controversies inherent in conventional animal experimental protocols [4]. By enabling interactive three-dimensional anatomical visualization, real-time feedback mechanisms, and self-regulated learning pace control (including module repetition and procedural acceleration), these systems provide pedagogically superior alternatives to physical laboratory equipment, allowing learners to achieve optimized knowledge acquisition and operational mastery through immersive virtual environments while maintaining cost-effectiveness and ethical compliance in biomedical education. As a cornerstone discipline for cultivating pharmaceutical service competencies, pharmacology education has long grappled with the critical deficiency of contextualized knowledge application scenarios. Conventional pedagogical approaches inadequately bridge theoretical concepts (including drug mechanisms, pharmacological effects, and adverse reactions) with clinical decision-making processes, resulting in a pervasive practice gap where students "understand pharmacology yet struggle with therapeutic applications". While existing virtual simulation technologies have been partially implemented in pharmacology instruction, current applications predominantly focus on visualizing complex drug mechanisms and simulating hazardous animal experiments, failing to encompass essential clinical pharmacy competencies such as prescription auditing, incompatibility identification, and medication counseling - all pharmacologically-relevant practice domains. In response to vocational college students' digital learning preferences and concrete cognitive patterns, our research team collaborated with tertiary hospitals to develop an innovative scenario-based, interactive, and scalable prescription dispensing virtual simulation system. This proprietary platform, constructed using authentic hospital pharmacy workflow data, meticulously simulates real-world prescription processing procedures, serving as an effective instructional aid across pharmacology and clinical pharmacotherapy curricula. This study pioneers the integration of prescription-focused virtual simulation into pharmacological didactics, demonstrating measurable improvements in educational outcomes through empirical implementation.

2. Instructional Design and Implementation

A total of 112 students from Class 1 and Class 2 (Grade 2023, Pharmaceutical Equipment Application Technology) at Chongqing medical and Pharmaceutical College were enrolled. Students were randomly allocated to control group (Class 1, n=56) and experimental group (Class 2, n=56) through a computer-generated randomization protocol, which employed Excel's RAND function to dynamically generate unique random numerical sequences, followed by a rank-ordering methodology based on stochastic assignment principles to ensure unbiased group stratification. No statistically significant differences were observed in prior academic performance between the two groups ($P > 0.05$), including scores in prerequisite courses such as Electronics and Applications, College English, Computer Applications, Mechanical Drawing and CAD, Medical Humanities, and Fundamental Chemistry for Pharmaceuticals. The Pharmacology course for Pharmaceutical Equipment Application Technology comprises 68 credit hours, including 10 hours of practical training and 58 hours of theoretical instruction. The theoretical component incorporates 2 hours of flexible scheduling and 2 hours of review and Q&A sessions.

During the first session for the experimental cohort, faculty members delivered comprehensive training on the prescription dispensing virtual simulation system's operational methodology, while explicitly informing students of their access to anonymized, unlimited self-paced practice modules post-curriculum—adaptive to individual learning patterns and knowledge assimilation progress—with the platform's intelligent tracking mechanism automatically capturing procedural learning footprints and generating context-specific feedback through real-time analytics engines during unstructured rehearsal activities. Two dedicated sessions were conducted: one during the mid-semester flexible period (2 credit hours) and another during the final review week (2 credit hours). Each session involved instructor-supervised virtual simulation practice, concluding with a 20-minute online test to evaluate knowledge application. Importantly, no monitoring or grading was applied to the students' self-directed practice activities or the final simulation test scores, ensuring these outcomes did not influence formative or summative assessments.

The virtual simulation system incorporated prescription categories and quantities as detailed in Table 1, comprehensively aligned with the pharmacological agents covered in theoretical lectures. During self-guided practice, students independently selected prescriptions, while the in-class online tests utilized automatically randomized prescriptions from the same disease categories and quantities. Critically, the self-practice prescriptions fully encompassed those used in the in-class tests.

The control group did not utilize the prescription dispensing virtual simulation teaching system. Both the 2 flexible hours and 2 review/Q&A sessions were conducted using traditional oral reviews and paper-based testing focused on key learning points. All other instructional content, teaching modes, pedagogical methods, and classroom management were standardized and delivered synchronously by the same instructor.

A unified final examination was administered to both groups at the end of the semester. Final academic performance evaluation comprised two weighted components: summative theoretical examination scores (60% weighting) and continuous assessment metrics (40% weighting). Both experimental and control groups maintained identical continuous assessment frameworks, systematically incorporating quantified measures of class attendance records, in-class interactive Q&A responses, routine homework assignment completion indices, and practical experiment evaluations — with explicit exclusion of virtual simulation autonomous rehearsal activities from the formative assessment algorithm. Statistical analysis of pharmacology exam scores was performed using SPSS 26.

This investigation constitutes a pedagogical efficacy evaluation, with all research data derived from anonymized academic records generated through standard instructional processes, devoid of sensitive personal identifiers or experimental interventions25. In accordance with stipulations delineated in the Ethical Review Measures for Biomedical Research Involving Human Subjects and institutional review board (IRB) operational guidelines, such minimal-risk educational investigations qualify for exemption from formal ethical review protocols.

3. Evaluation of Teaching Effectiveness

At the end of the semester, all students from both the experimental and control groups participated in a standardized final theoretical examination organized by the institution. The theoretical examination questions were developed by course instructors through rigorous selection from the standardized test bank, strictly following the teaching plan. The assessment comprehensively covered major pharmaceuticals discussed in lectures, featuring moderate difficulty levels and appropriate question quantity. Using SPSSAU for test analysis, the Cronbach's alpha coefficient was calculated as 0.898, indicating strong reliability nearing excellence. Validity analysis of both subjective and objective question scores yielded a KMO value of 0.875, confirming satisfactory validity. All performance metrics were statistically analyzed using SPSS 26, with results outlined below.

3.1. Descriptive Statistics

The course instructor uniformly assessed the regular academic performance of all students in the experimental group and the control group. All students completed the final examination, while the experimental group additionally engaged in 4 credit hours of virtual simulation training for prescription dispensing, including in-class assessments. Key descriptive statistics for both groups are presented in Table 1.

Table 1. Performance Statistics for Control and Experimental Groups

Category	N	Range	Min	Max	Mean	Std. Deviation	Variance
Control Group (Final)	56	32	61	93	75.89	6.912	47.770
Control Group (Regular)	56	20	80	100	94.16	5.008	25.083
Experimental Group (Regular)	56	20	80	100	94.61	4.927	24.279
Experimental Group (Final)	56	30	68	98	81.46	7.178	51.526
Valid Cases (Listwise)	56						

3.2. Analysis of Data Distribution Characteristics

To select appropriate statistical methods, a preliminary analysis of data distribution characteristics was conducted. Given the small sample size (n=56), the Shapiro-Wilk (S-W) test was applied for normality assessment. Results indicated: Non-normal distributions for formative scores in both the experimental and control groups ($p<0.05$). Normal distributions for final scores in both groups ($p>0.05$). Comprehensive normality test results are presented in Table 2.

Table 2. Normality Test Results for Control and Experimental Groups

Variable	*Kolmogorov-Smirnov (K-S) Testa*			*Shapiro-Wilk Test*		
	Statistic	df	Sig.	Statistic	df	Sig.
Final Scores (Control)	0.065	56	0.200*	0.993	56	0.990
Quiz Scores (Control)	0.245	56	0.000	0.869	56	0.000
Quiz Scores (Experimental)	0.246	56	0.000	0.858	56	0.000
Final Scores (Experimental)	0.077	56	0.200*	0.981	56	0.523

Notes: *: Lower bound of true significance; a: Lilliefors significance correction applied.

3.3. Analysis of Differences in Formative and Final Scores Between Experimental and Control Groups

To select appropriate statistical methods, a preliminary analysis of data distribution characteristics was conducted. Given the small sample size (n=56), the Shapiro-Wilk (S-W) test was applied for normality assessment. Results indicated: Non-normal distributions for formative scores in both the experimental and control groups ($p<0.05$). Normal distributions for final scores in both groups ($p>0.05$). Comprehensive normality test results are presented in Table 3.

3.4. Analysis of Data Distribution Characteristics

The formative scores of both groups exhibited non-normal distributions; thus, an Independent Samples Kruskal-Wallis Test was performed. Results indicated no significant difference in formative scores between the experimental and control groups ($p>0.05$) (Table 3).

Table 3. Kruskal-Wallis Test Results for Formative Scores

Metric	*Value*
Total Sample Size (N)	112
Test Statistic	0.280ab
Degrees of Freedom (df)	1
Asymptotic Significance (2-tailed)	0.597

Notes: a. The test statistic was adjusted for tied values to ensure accuracy in non-parametric analyses.
b. Since the overall test did not detect significant differences between groups ($p > 0.05$), post hoc multiple comparisons were deemed unnecessary and thus omitted.

For final scores, which followed normal distributions, an Independent Samples T-Test was applied. The experimental group demonstrated significantly higher final scores than the control group ($p<0.01$) (Table 4).

Table 4. Independent Samples T-Test Results for Final Scores

Test Category	*F*	*Sig.*	*t*	*df*	*Sig. (Two-tailed)*	*Mean Difference*	*Std. Error Difference*	*95% Confidence Interval*
Final Scores (Equal Variances Assumed)	0.003	0.956	-4.048	110	0.000	-5.232	1.293	-7.794 to -2.671
Final Scores (Equal Variances Not Assumed)	—	—	-4.048	110	0.000	-5.232	1.293	-7.794 to -2.671

3.5. Correlation Analysis Between Virtual Simulation Scores in Prescription Dispensing and Final Scores

To further analyze the impact of the virtual simulation course in prescription dispensing on final exam performance, a Pearson correlation analysis was conducted using SPSS 26 to examine the relationship between the experimental group's virtual simulation scores and their final scores. Results revealed a statistically significant positive correlation between the two variables ($p<0.05$) (Table 5), indicating that the application of the virtual simulation teaching system effectively improved student outcomes.

Table 5. Pearson Correlation Results for Virtual Simulation Scores and Final Scores

Variable	*Final Scores*	*Virtual Simulation Scores*
Final Scores		
Pearson Correlation	1	0.432**
Sig. (2-tailed)	—	0.001
Total Sample Size (N)	56	56
Virtual Simulation Scores		
Pearson Correlation	0.432**	1
Sig. (2-tailed)	0.001	—
Total Sample Size (N)	56	56

Notes:**. Correlation is significant at the 0.01 level (2-tailed).

4. Conclusions and Discussion

4.1. Application of the Virtual Simulation Prescription Dispensing System Enhances Students' Theoretical Pharmacology Performance

While virtual simulation systems hold significant potential in pharmaceutical education, their adoption still lags behind other medical disciplines. Current research predominantly focuses on medical or nursing applications, with relatively scarce utilization in pharmaceutical education studies. The implementation of virtual simulation teaching systems in pharmacology instruction remains particularly limited[5].Both domestic and international research highlights that virtual simulation technology in pharmacy education is predominantly applied to high-risk experiments[6] , complex procedures[7] , and scenario-based skill training[8] .Compared to traditional methods, virtual simulations offer dynamic, immersive learning experiences that transcend time and space constraints, effectively stimulating student engagement and improving comprehension of abstract theoretical concepts[9] . Abdel Haleem et al. applied a virtual computer tool simulating real pharmacological lab equipment in a large-scale basic medical course during its second semester. Student surveys showed nearly half acknowledged its reinforcement of theoretical knowledge, with instructors and most students endorsing the virtual simulation learning model as an effective teaching/learning aid [10].

In theoretical teaching, virtual simulations have been reported to clarify complex pharmacological mechanisms and pharmacodynamic principles. However, standalone applications of virtual prescription dispensing systems in pure theoretical pharmacology teaching remain unexplored. Liu xiaodong (2019) demonstrated that integrating pharmacodynamic virtual simulations into pharmacology courses enriched teaching content, boosted student interest, and enhanced theoretical and practical competencies, thereby advancing pedagogical reforms [11].

This study introduced the virtual simulation prescription dispensing system into pharmacology review sessions. Pharmacology courses involve extensive drug classifications, with a focus on mechanisms, clinical applications, adverse effects, and drug interactions—a challenging knowledge system for students [12]. The system's case-based prescriptions required students to apply pharmacological knowledge from key chapters, naturally directing attention to core concepts and fostering interdisciplinary integration. Traditional review sessions, though critical for final exams, often lead to student disengagement due to repetitive teacher-led emphasis on key points.

The prescription dispensing virtual simulation teaching system enhances student engagement through immersive environments, allowing self-paced practice of prescription review, dispensing, and medication guidance without clinical risks. This approach provides exploratory autonomy, fostering clinical thinking alongside subject mastery [13]. With only 4 classroom hours for the experimental group, the system's immediate feedback mechanism reduced cognitive load and improved efficiency [14], aligning with findings from nursing education [15]. Virtual simulation not only reinforces drug theories but enables safe practice exploration, where interactive experiences and feedback stimulate interest, cultivate self-directed learning, and enhance medication safety awareness—directly supporting pharmacy education's goal of developing comprehensively skilled professionals.

4.2. Constructing a Digital Education Ecosystem and Innovating Smart Classroom Management

Global pharmacy education now prioritizes a "competency-digital literacy-lifelong learning" trinity, with digital proficiency recognized as the sixth core competency by the International Pharmaceutical Federation (FIP). Current "digital native" learners widely expect deep integration of digital technology in education [16]. The COVID-19 pandemic accelerated pharmaceutical education's digital transformation [17-18], driving institutions to adopt, research, and optimize virtual simulation teaching systems [19]. Prescription dispensing virtual simulation software aligns with FIP's global digital competency framework and reshapes pharmaceutical talent training through a "context-embedded, data-driven, precision-intervention" teaching model. Integrating virtual prescription dispensing exercises into pharmacology courses exemplifies this shift, demonstrating how data-driven pedagogy enriches intelligent education frameworks. The application of prescription dispensing virtual simulation software in pharmacology courses offers replicable technical pathways and empirical evidence for implementing "data-driven intelligent education" in pharmaceutical fields.

4.3. Limitations

This study has several limitations. The condensed course timeline restricted comprehensive evaluation of long-term knowledge retention, making it difficult to assess impacts on subsequent core curricula or career outcomes. The small sample size may compromise generalizability, while online assessment scores fail to fully capture students' holistic competency gains from virtual dispensing simulations. Future directions include systematically integrating virtual training modules into Pharmacology and Clinical Pharmacotherapy courses across multiple cohorts, extracting simulation process data for formative evaluations to map progressive skill development. To gauge sustained clinical decision-making impacts, we will collaborate with graduates' employers to establish career progression databases and track pharmaceutical knowledge application through tripartite surveys (graduates, employers, patients), thereby evaluating workplace integration of simulation-acquired expertise.

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An Empirical Study on the Impact Mechanism of Medical Students' Learning Outcomes from the Perspective of Learning Engagement

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Abstract. Based on the theory of learning engagement, this study employs the "China College Student Survey" (CCSS) questionnaire and structural equation modeling (SEM) to empirically investigate the impact mechanism of medical students' learning outcomes. The findings reveal that five factors— "Active and Collaborative Learning", "Student and Faculty Interactive", "Academic Challenge level", "Supportive Campus Environment" and "Enriched Educational Experiences"—directly or indirectly influence medical students' learning outcomes. Among these, the "Supportive Campus Environment" exerts the strongest impact, while the "Enriched Educational Experiences" show relatively weaker effects. Accordingly, recommendations include strengthening campus environment construction, scientifically designing curricula based on academic challenge levels, fostering harmonious campus relationships, and establishing incentive mechanisms to encourage medical students' participation in practical activities.

Keywords. Medical students; Educational quality; Learning engagement; CCSS; Learning outcomes

1. Introduction

Medical education serves as a cornerstone for the development of public health, bearing the critical responsibility of cultivating professionals for the healthcare sector. Exploring how to ensure and enhance the quality of medical education is of paramount significance. Current research on educational quality is gradually shifting from macro to micro perspectives, focusing on individual student development to evaluate

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educational effectiveness. Learning engagement refers to the time and effort students invest in effective learning activities, as well as their perceptions of institutional support for their learning [1]. This study centers on improving medical education quality by examining the relationship between learning engagement and learning outcomes, aiming to provide insights for advancing medical education practices.

2. Research Hypotheses

Research on learning engagement in China has a relatively short history and has developed slowly. The research team led by Tsinghua University developed the China College Student Survey (CCSS). Existing studies on the mechanisms of how learning engagement influences learning outcomes indicate that various dimensions of learning engagement measured by the CCSS questionnaire—specifically, “Level of Academic Challenge” (LAC), “Active and Collaborative Learning” (ACL), “Student and Faculty Interactive” (SFI), “Enriched Educational Experiences” (EEE), and “Supportive Campus Environment” (SCE)—can predict learning outcomes. For instance, Li Xiongying et al. demonstrated that learning engagement among students in the “Elite Program” significantly and positively influences learning outcomes [2]. Xing Quanchao revealed the interactive relationship between undergraduate students’ learning engagement and academic performance, highlighting the significant impact of “supportive campus environment” and “Enriched Educational Experiences” on academic achievement [3]. Regarding the content of these dimensions: Academic challenge level refers to the rigor of course requirements and the demands placed on students’ time and effort. Supportive campus environment assesses the support provided by institutions and staff for learners during academic activities. Active and collaborative learning measures students’ proactive participation and collaboration in learning activities. “Student and Faculty Interactive” evaluates the frequency and depth of communication between learners and instructors. “Enriched Educational Experiences” investigates the breadth and diversity of learners’ educational experiences [4]. Based on this, the study proposes the following research hypotheses:

H1: All dimensions of medical students’ learning engagement directly and positively influence their learning outcomes.

The environment acts as a “black box” that drives changes in students’ competencies and serves as the external starting point for improving learning outcomes. Environmental factors not only exert a direct and powerful impact on students’ growth but also indirectly cultivate their competencies by enhancing their engagement [5]. From the perspective of environment and individual factors, “Supportive Campus Environment” and “Level of Academic Challenge” belong to external environmental influences on learning. Specifically, the “Supportive Campus Environment” reflects the macro-environment, while “Level of Academic Challenge” focuses on curriculum rigor as a micro-environment. “Active and Collaborative Learning”, “Student and Faculty Interactive”, and “Enriched Educational Experiences”, however, pertain to students’ individual learning processes. Based on this, the study proposes the following hypotheses:

H2: The “Supportive Campus Environment” indirectly influences medical students’ learning outcomes through “Level of Academic Challenge”, “Active and Collaborative Learning”, “Student and Faculty Interactive”, and “Enriched Educational Experiences”.

H3: "Level of Academic Challenge" indirectly influences medical students' learning outcomes through "Active and Collaborative Learning", "Student and Faculty Interactive", and "Enriched Educational Experiences".

Teaching is a bidirectional interactive process between instructors and students. The relationship between teachers and students significantly shapes learners' attitudes, interests, styles, and behaviors [6]. Thus, the study hypothesizes:

H4: "Student and Faculty Interactive" indirectly influences medical students' learning outcomes through "Active and Collaborative Learning" and "Enriched Educational Experiences".

Modern educational psychology posits that learning motivation is the psychological drive derived from learners' value judgments of their learning behaviors [7]. Learning motivation regulates learning activities through initiation, orientation, guidance, maintenance, adjustment, reinforcement, and sublimation [8]. Greater motivation leads to more sustained and stable engagement in learning. "Active and Collaborative Learning" reflects students' attitudes and proactive participation. Accordingly, the study proposes:

H5: "Active and Collaborative Learning" indirectly influences medical students' learning outcomes through "Enriched Educational Experiences".

3. Research Design

3.1 Methodology

This study selected relevant indicators from the CCSS questionnaire to form the survey tool. The preliminary scale for medical students' learning engagement comprised 47 items, including 11 items on "Active and Collaborative Learning", 9 on "Level of Academic Challenge", 5 on "Student and Faculty Interactive", 10 on "Supportive Campus Environment", and 12 on "Enriched Educational Experiences". The preliminary scale for learning outcomes included 15 items. The questionnaire adopted a 4-point Likert scale with positive scoring: Frequency-based items: 1 = Never, 2 = Sometimes, 3 = Often, 4 = Very Often; Emphasis-based items: 1 = Not Emphasized, 2 = Slightly Emphasized, 3 = Emphasized, 4 = Strongly Emphasized; Action-based items: 1 = Undecided, 2 = Not Planning, 3 = Planning, 4 = Already Done.

3.2 Sample

This study employed grade-stratified random sampling for participant recruitment, utilizing the Questionnaire Star platform for data collection. Through established professional networks, the survey was distributed via WeChat and QQ groups affiliated with medical colleges in Guangdong, Zhejiang, Beijing, and adjacent regions during March-April 2022. A total of 1,008 responses were collected. After removing invalid data (e.g., outliers, missing values), 970 valid questionnaires were retained, yielding an effective rate of 96.23%. The sample exhibited good heterogeneity: Gender: Male (43.19%), Female (56.81%). Grade distribution: Year 1 (23.81%), Year 2 (24.23%), Year 3 (21.86%), Year 4 (18.04%), Year 5 (12.06%). Geographic origin: Domestic students (57.01%), International students (42.99%).

3.3 Statistical Tools

Data were input into SPSS 26.0 for preliminary analysis and organization, including missing value analysis and handling, item analysis, exploratory factor analysis (EFA), correlation analysis, and reliability analysis. Amos 26.0 was used for confirmatory factor analysis (CFA) to test the construct validity of both questionnaire sections. After revising the questionnaire, descriptive statistics, mean calculations, and comparisons were conducted using the refined variables. Correlations between variables were analyzed, and a structural equation model (SEM) was constructed to explore the impact of medical students' learning engagement on their learning outcomes.

4. Empirical Analysis

4.1 Overall Learning Status of Medical Students

As shown, medical students' learning engagement (2.55 ± 0.40) and learning outcomes (2.60 ± 0.62) were generally at a moderate level. Ranking the dimensions of learning engagement by mean scores from highest to lowest: "Supportive Campus Environment" (3.02 ± 0.52), "Level of Academic Challenge" (2.74 ± 0.63), "Active and Collaborative Learning" (2.53 ± 0.51), "Enriched Educational Experiences" (2.39 ± 0.66), "Student and Faculty Interactive" (1.76 ± 0.68).

4.2 Path Analysis of the Impact of Learning Engagement on Learning Outcomes

Structural equation modeling (SEM) facilitates the examination of complex interrelationships between multiple dependent and independent variables, transcending the constraints inherent in conventional regression analysis. Therefore, to further investigate the relationships between the dimensions of medical students' learning engagement and their learning outcomes, this study employed Amos 26.0 to construct a structural equation model (SEM) of the influencing pathways. Non-significant paths were removed, and significant paths were retained, resulting in the finalized structural model (M3). The path diagram of the model is shown in Figure 1.

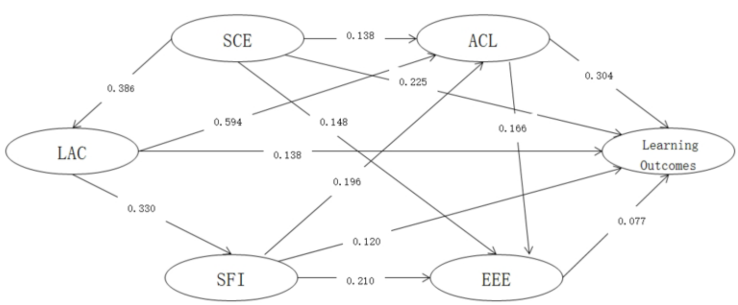

Figure 1. Structural Equation Model (SEM) of Pathways Influencing Medical Students' Learning Outcomes

From the model in Figure 1, the influencing factors, pathways, and structural relationships among variables affecting medical students' learning outcomes can be clearly observed. According to the path analysis in Figure 1, all five dimensions of medical students' learning engagement have "direct effects" on learning outcomes. As shown, the direct effect sizes of these dimensions, ranked from largest to smallest, are: "Active and Collaborative Learning", "Supportive Campus Environment", "Level of Academic Challenge", "Student and Faculty Interactive", "Enriched Educational Experiences".

Notably, in this model, "Active and Collaborative Learning", "Student and Faculty Interactive", "Level of Academic Challenge", and "Supportive Campus Environment" also exert "indirect effects" on learning outcomes by influencing other factors, in addition to their direct effects. For example: "Supportive Campus Environment" indirectly impacts learning outcomes through its direct positive effects on "Level of Academic Challenge", "Enriched Educational Experiences", and "Active and Collaborative Learning". "Level of Academic Challenge" indirectly influences learning outcomes via its direct positive effects on "Student and Faculty Interactive" and "Active and Collaborative Learning". "Student and Faculty Interactive" indirectly affects learning outcomes through its direct positive effects on "Active and Collaborative Learning" and "Enriched Educational Experiences". "Active and Collaborative Learning" indirectly contributes to learning outcomes through its direct impact on "Enriched Educational Experiences".

However, the correlations between "Supportive Campus Environment" and "Student and Faculty Interactive", as well as between "Level of Academic Challenge" and "Enriched Educational Experiences", were not statistically significant. As shown in Table 1, the total effects of the five dimensions are ranked as follows (from largest to smallest): "Supportive Campus Environment", "Level of Academic Challenge", "Active and Collaborative Learning", "Student and Faculty Interactive", "Enriched Educational Experiences".

Table 1. Standardized Coefficients of the Effects of Medical Students' Learning Engagement Variables on Learning Outcomes

Variable Noun	Direct Effect	Indirect Effect	Total Effect
ACL	0.304	0.013	0.317
SFI	0.120	0.078	0.198
LAC	0.138	0.254	0.392
SCE	0.225	0.206	0.431
EEE	0.077	-	0.077

5. Research Conclusions and Implications

5.1 Research Conclusions

5.1.1 Medical students' learning engagement positively impacts their learning outcomes.

Empirical data from this study demonstrate that medical students' learning engagement can positively predict their learning outcomes. This is consistent with the findings from other groups [9]. Among the dimensions, the "Supportive Campus Environment" exerts the strongest influence. This may be attributed to the fact that medical education, compared to other disciplines, relies more heavily on institutional resources and policy support. For instance, medical training requires extensive equipment, pharmaceuticals, chemical reagents, and a longer curriculum with more practical components, making it one of the most resource-intensive fields. On the other hand, the weaker impact of "Enriched Educational Experiences" on learning outcomes may not reflect inherent limitations of this dimension but could stem from insufficient institutional efforts to provide activities and platforms aligned with medical students' learning needs, thereby limiting opportunities for enriched experiences.

5.1.2 The relationship between learning engagement and learning outcomes is complex, involving both direct and mediated pathways.

The study reveals that all dimensions of learning engagement directly enhance learning outcomes. Additionally, "Level of Academic Challenge", "Active and Collaborative Learning", "Student and Faculty Interactive", and "Enriched Educational Experiences" act as partial mediators. These results align with those reported by Wang S. in studies focusing on research university students [10]. For example, "Student and Faculty Interactive" indirectly improves learning outcomes by fostering active collaboration. Prior research indicates that high-quality teacher-student interactions motivate students and enhance their engagement levels [11]. In essence, stronger communication between medical students and instructors stimulates proactive learning attitudes, thereby elevating learning outcomes.

5.1.3 Medical students' learning engagement remains suboptimal.

Overall, the average score for medical students' learning engagement was 2.55 (out of 4). Except for the "Supportive Campus Environment" (3.02), none of the other four dimensions exceeded 3 points, indicating weak engagement in academic and practical educational activities. Notably, "Student and Faculty Interactive" scored the lowest (1.76), reflecting insufficient meaningful engagement between students and teachers—a finding consistent with Liu Fahu et al.'s conclusions [12].

5.2 Research Implications

5.2.1 Prioritize Medical Education and Enhance Academic Support

Higher education institutions must cultivate medical students through integrated support systems: customized academic/mental health/career/financial assistance; modernized clinical training via upgraded simulation labs and teaching hospitals; resilience-building workshops and counseling; career navigation with licensing exam prep (e.g., USMLE) and specialty pathways; and humanistic education through medical ethics and patient communication curricula to develop competent, compassionate practitioners.

5.2.2 Optimize Curriculum Design Using Vygotsky's Zone of Proximal Development (ZPD)

Lev Vygotsky's ZPD theory posits that appropriately challenging curricula can unlock students' latent potential, enabling them to advance from their current capabilities to higher developmental levels, which then serve as foundations for continuous dynamic progression [13]. Therefore, medical educators should: Align teaching objectives and content with students' existing competencies to avoid curricula that are either too simplistic or exceed learners' developmental potential. Precisely design learning goals, content, and key challenges to stimulate engagement, leverage students' potential, and bridge the gap between their current abilities and targeted developmental milestones. Foster active learning by encouraging students to transcend their immediate ZPD and achieve higher levels of professional competence.

5.2.3. Enhance Interaction Quality Between Students and Faculty, and Foster Harmonious Campus Relationships

To address limited and suboptimal interactions among medical students and between learners and faculty, institutions should implement comprehensive strategies across curricular and extracurricular domains. Curricular modifications should transition from conventional lecture-dominated instruction to interactive learning frameworks that facilitate peer-instructor partnerships. Beyond classroom settings, structured extracurricular programs—including academic competitions, professional clubs, and community-based practicums involving cross-disciplinary collaboration—should be regularly organized to mitigate social barriers and foster collaborative academic relationships. Furthermore, academic departments should institutionalize rotational leadership systems within student organizations, creating successive opportunities for medical trainees to develop administrative competencies through participatory governance roles. This tripartite approach synergistically enhances engagement while cultivating essential professional skills.

5.2.4. Promote Practice-Oriented Education to Encourage Extracurricular Learning

Universities should align practical training systems with medical students' learning needs and professional requirements: Hospital partnerships: Collaborate with healthcare institutions to reform curricula, teaching methods, and practical training, ensuring alignment with medical career competencies and licensure standards. Digital learning platforms: Utilize modern educational technologies to establish virtual labs and simulation platforms for self-directed and personalized learning. Hands-on activities: Expand extracurricular medical competitions (e.g., nursing skills challenges, comprehensive competency contests) to stimulate proactive learning and skill development. Community service: Organize regular volunteer programs (e.g., rural health outreach, summer/winter social practices, "Three Rural Initiatives" campaigns) to expose students to real-world challenges while honing their technical expertise.

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Modern Management based on Big Data VI
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Research on the Application of Big Data in Ideological and Political Education in Guangxi Universities in the New Era

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Abstract. The emergence of the wisdom teaching model addresses the triple imperatives of social progress, educational evolution, and holistic human development. This innovative approach leverages smart technologies to create adaptive learning ecosystems that prioritize learner autonomy and value internalization. Our research developed an APH-based evaluation framework for ideological and political education (IPE), enabling systematic assessment of multi-dimensional learning outcomes. Complementing this, we built an integrated online platform featuring personalized content delivery, interactive simulations, and AI-driven feedback mechanisms. Pilot studies with 823 students across two cohorts demonstrated significant cognitive gains (Cohen's d = 0.78) and enhanced self-directed learning capacities, with 89% reporting improved competencies. The findings validate the model's effectiveness in fostering informed, ethically grounded digital citizens through technology-enhanced pedagogy.

Keywords. Computer big data technology; Guangxi universities; college students; ideological and political education system

1. Introduction

The ideological and political education in Chinese colleges and universities bears the important task of “building morality and cultivating people”, which affects the improvement of Chinese comprehensive strength and the realization of national rejuvenation. However, due to the variability of current educational objects, the broadness of educational content, the complexity of ideological issues, and the diversity of ideological needs, ideological and political education in colleges and universities has shown weaknesses in its isolation and simplification of educational models. According to the theory of synergy, no single element alone can undertake all of the ideological and political education in colleges and universities [1]. Only when it has a joint role with other subsystems can the best effect of the structure be brought into play. Under contemporary social conditions, the coordination of ideological and political education in universities is not only a theoretical research topic but also a prominent educational practice issue.

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To address these challenges, this paper proposes a comprehensive approach to enhancing ideological and political education (IPE) in Guangxi universities through the application of big data technology. The paper is structured as follows: Firstly, we provide a theoretical framework that integrates the elements of the macro system, meso system, and micro system that affect IPE in colleges and universities. Based on this framework, we explore multiple synergy modes such as teaching, process, learning, department, and environment. Next, we introduce the big data ideological and political education model, which leverages big data and statistical analysis to implement a scientific, precise, three-dimensional, personalized, and real-time IPE model.

The paper then proceeds to describe the methodology employed in developing an APH-based evaluation framework for IPE. This framework enables systematic assessment of multi-dimensional learning outcomes. Complementing this, we detail the design and implementation of an integrated online platform featuring personalized content delivery, interactive simulations, and AI-driven feedback mechanisms. The efficacy of this model is validated through pilot studies conducted with 823 students across two cohorts, which demonstrate significant cognitive gains and enhanced self-directed learning capacities.

Finally, the paper concludes by discussing the implications of the findings for fostering informed, ethically grounded digital citizens through technology-enhanced pedagogy, and highlights areas for future research.

Based on the theory of synergy, this article organically connects and integrates the elements in the macro system, meso system, and micro system that affect ideological and political education in colleges and universities, constructing multiple synergy modes and exploring the realization of each collaborative model. This constitutes a three-dimensional and chain-shaped optimization system for ideological and political education in colleges and universities.

This introduction sets the stage for the rest of the paper by outlining the theoretical foundation, research methodology, and practical application of big data in ideological and political education in Guangxi universities.

2. The connotation of the big data ideological and political education model

The big data ideological and political education model refers to the complete, rich, real-time and dynamic data collected by different data systems based on the theory of big data theory, statistics, computer science, educational technology, pedagogy, psychology and other disciplines. Big data and statistical analysis, so as to implement a scientific, precise, three-dimensional, personalized, and real-time ideological and political education model for the educated, which is scientific, forward-looking, time-effective, subjective, and personalized Intrinsic attributes [2]. The purpose and goal of the construction of the big data ideological and political education model is to deeply integrate the theory and technology of big data into the whole process of ideological and political education to solve the problem of the effectiveness of ideological and political education. 3. Determining the weights of “grade theme” and “basic” factors based on analytic hierarchy process Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method proposed in the 1970s. The analytic hierarchy process is suitable for multi-objective decision-making problems with complex hierarchical structure, can deal with the qualitative and quantitative factors in decision-making in a unified way, and has the advantages of practicability, system city, simplicity and so on. The basic steps of the analytic hierarchy process are as follows:

3. The basic steps of the ideological and political education practice project

3.1 Establish a hierarchical structure model

According to the “Opinions” on the content of college students' ideological and political education, determine the set of factors for the evaluation of college students' ideological and political education content, and establish a secondary level of judgment. Use Table 1 to express it as follows:

Table 1. Set of factors for college students' ideological and political education

Target layer	Index layer	Child
Various themes of ideological and political education	Ideal and Belief Education	“Three Views” Education, Advanced Theory Education, Practical Education
	Patriotism education	Revolutionary traditional education, the cultivation of national spirit, and the basics of practical education
	Moral education	Integrity education, respecting the old and loving the young, and fostering social ethics
	Innovative education	Cultivation of scientific research awareness, scientific spirit, and innovative ability
	Other	Legal education, fostering education, professional ethics training, psychological quality education

Taking a university as the research object, the author conducted correspondence consultations with ideological and political education experts, students’ parents, and students. All grades consulted and filled in according to the content designed in Table 1 and the blank form designed in Table 3 below. A, B, C, D, and E are selected by the client independently and autonomously according to the first feeling according to any one of the items in Table 1. 30 people were consulted at each level, including 15 experts, 10 parents, and 5 students. The consultation statistics are shown in Table 2:

Table 2. Consultation statistics results

Grade	**Number of copies**				**Percentage of 40 shares**
	expert	Parent	student	total	
First grade	13	5	3	21	70%
Second grade	13	5	3	19	63%
Third grade	13	5	3	24	80%
Fourth grade	13	6	4	23	77%
Grade	Common factors				
	A	B	C	D	E
First grade	Ideals and beliefs	Patriotism	Honesty	Psychological quality education	Formation education
Second grade	Ideals and beliefs	Patriotism	Honesty and trustworthiness and social ethics	Psychological quality education	Love view
Third grade	Ideals and beliefs	patriotism	Honesty	Creativity	Professional quality education
fourth grade	Ideals and beliefs	patriotism	Honesty and professional ethics	Scientific spirit and innovative ability	social practice

3.2 Constructing the judgment matrix

The construction of the judgment matrix is a key step of AHP, that is, to compare the relative importance of the elements in the bottom layer, that is, to compare the relevant elements in the layer pair by pair, and to quantify the comparison results according to a certain ratio scale, to form a judgment matrix. The method of constructing the judgment matrix used in this paper is the scale method of 1-9 and its reciprocal [3]. We take the first grade as an example to use the analytic hierarchy process to analyze the consultation results (choose an expert consultation form from the 18 forms with the same options):

Table 3. Expert Consultation Form

Index	A	B	C	D	E
A	1	3	5	5	3
B	1/3	1	3	3	2
C	1/5	1/3	1	2	1
D	1/5	1/3	1/2	1	1
E	1/3	1/2	1	1	1

Construct a judgment matrix:

$$A=\begin{bmatrix} 1 & 3 & 5 & 5 & 3 \\ 1/3 & 1 & 3 & 3 & 2 \\ 1/5 & 1/3 & 1 & 2 & 1 \\ 1/5 & 1/3 & 1/2 & 1 & 1 \\ 1/3 & 1/2 & 1 & 1 & 1 \end{bmatrix} \tag{1}$$

3.3 Level weight and its consistency check

According to the judgment matrix to calculate the relative weight of the hierarchical index items, mathematically, it boils down to the problem of calculating the maximum eigenvalue of the judgment matrix and its corresponding eigenvector. Its function is to test the rationality of the judgment [4]. When the judgment is reasonable, each column vector of the consistency matrix is an eigenvector. After the eigenvector is standardized, it is recorded as $W=\left(w_1, w_2, ..., w_3\right)^T$, which satisfies

$$\Sigma_{i=1}^{n} w_i = 1 \tag{2}$$

Among them, W is called the weight vector, which represents the proportion of each factor in the target. The index to measure the degree of inconsistency is defined as:

$$CI=\frac{\lambda_{max}-n}{n-1} \tag{3}$$

The higher the consistency of the judgment matrix, the smaller the CI value, and the judgment matrix is completely consistent. The eigenvector of the judgment matrix is:

[0.47202, 0.22863, 0.10678, 0.08092, 0.11165].

We use the same method to calculate the eigenvectors of the judgment matrices of the remaining 12 experts, and take the average value of the eigenvectors of the judgment matrices of 13 experts: [0.45001, 0.19723, 0.10521, 0.08100, 0.16655].

According to the same method, the average value of the eigenvectors of the judgment matrix of 5 parents of students is calculated as: [0.40601, 0.20145, 0.11436, 0.09721, 0.18097].

The average of the eigenvectors of the judgment matrices of 3 students is: [0.39001, 0.21056, 0.13561, 0.11230, 0.15152].

The calculation results of experts, parents, and students are respectively weighted as 0.5, 0.3, 0.2 (adjustable according to the survey object), and each item is added to obtain the eigenvector of the judgment matrix: [0.42481, 0.20207, 0.11403, 0.09212, 0.16697]. That is the factors in the factor set {A, B, C, D, E} are judged.

The weights (in percentage) of the various factors of the ideological and political education of the first-year university students are: A (ideal and belief), accounting for 42.481%; B (patriotism), accounting for 20.207%; C (honesty and trustworthiness), accounting for 11.403%; D (humanistic quality and scientific spirit), accounting for 9.212%; E (cultivating education), accounting for 16.697%.

According to the same method, the weights of the various factors of the ideological and political education of students in different grades are as follows: second grade: A (ideal and belief), accounting for 39.630%; B (patriotism), accounting for 21.308%; C (honesty and trustworthiness and social ethics), Accounting for 13.472%; D (humanistic quality and scientific spirit), accounting for 15.236%; E (love concept), accounting for 10.354%.

The third grade: A (ideal and belief), accounting for 38.721%; B (patriotism), accounting for 20.378%; C (honest and trustworthy), accounting for 11.230%; D (scientific spirit and innovative ability), accounting for 17.235%; E (professional quality), accounting for 12.436%.

Fourth grade: A (ideal and belief), accounting for 35.276%; B (patriotism), accounting for 20.253%; C (honesty and trustworthiness and professional ethics), accounting for 23.251%; D (scientific spirit and innovative ability), accounting for 12.436%; E (Social practice), accounting for 8.784%.

4. System Design

4.1 System operating environment

To build a network party building education system based on the B/S model, you need to use a three-tier browser/server (B/S) structure, and use .NET4.0 combined with C# programming to develop server-side applications. The server operating system is Windows 2003 Server, the database uses SQL Server 2008, the Web server is IIS6.0 and above, the application access to the database is realized through ADO.NET technology. The interface design and production use HTML5 and CSS3 coding technology, and the hardware configuration of the system running server is I7CPU (8G memory), the network bandwidth is required in the environment of the campus network.

4.2 System structure

The specific functions of the system modules are divided mainly based on user identity. The system administrator's responsibilities are as follows: maintain basic information (student information, college information), provide articles that students are required to read, upload videos of party knowledge that students are required to watch, and determine test subjects and create a test question bank, open training classes, select the articles that need to be read, watch videos, and test subjects [5]. The responsibilities of the second-level college administrator are as follows: release information and documents about the second-level college, and correct the students’ learning experience about the party’s knowledge, View the learning situation of the second-level college student training class. The permissions of the students are as follows: select the training class to participate in, enter the training class to read articles, watch the video of party knowledge, and take the exam; browse the information and files of the second-level college, and submit the learning experience of party knowledge. The system structure is shown in Figure 1 (the picture is quoted from Political Ideology: Its Structure, Functions, and Elective Affinities).

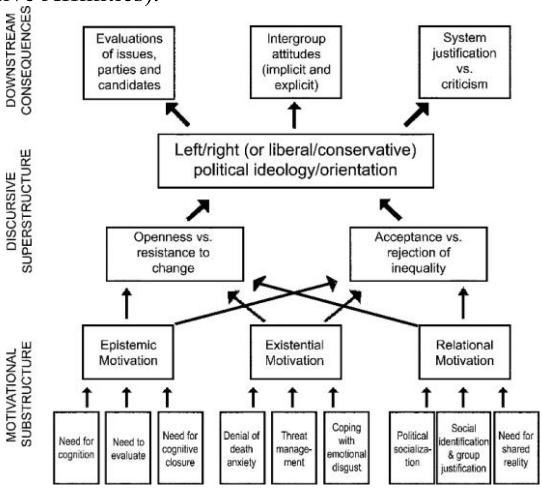

Fig. 1. System framework diagram

4.3 System process analysis

After party school students log on to the online party school, they judge its legitimacy. Enter the unit knowledge learning, after each unit learning is completed, a test is performed, and the test pass indicates that the unit knowledge learning has passed. After passing N units of study, enter the examination link. The online party school sets up two examination opportunities to take the record of the higher test scores, and compare it with the completion standard set by the online party school [6]. If the completion standard is greater than the completion standard, pass the exam and complete the course. the process is shown in Figure 2 (picture quoted from A Survey on the Effectiveness of Online Teaching–Learning Methods for University and College Students).

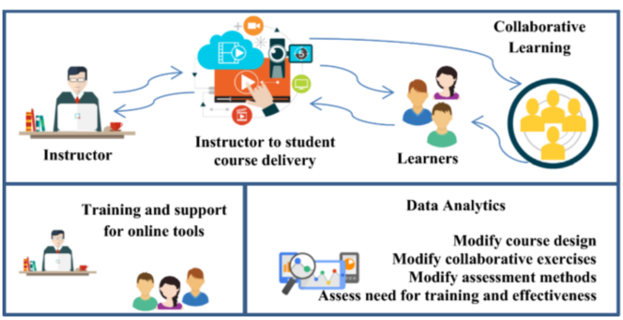

Fig. 2. Online party school learning test assessment process

4.4 Functional module design

The online party school online exam is the core module of the entire online party school. The overall implementation process is shown in Figure 3: Party school students enter their student ID and password to enter the online party school, study by unit and pass the unit practice test, then enter the assessment link. At this time, the system uses the Session the variable to record the information of the party school students, and submits a request to the server to enter the online examination subsystem. In the online party school online exam sub-module, in order to facilitate the operation of the party school students' exams, all the online exams select the panoramic mode to display the test papers. In order to prevent disoperation and submission of test papers, the online test sub-module has a test paper submission prompt confirmation function [7]. When the user submits the test paper, a test paper submission prompt will be given. After the submission is successful, the online party school automatically counts the examination results, and judges whether the examination has passed the examination according to the eligibility criteria set by the party school administrator. Each student has two exam opportunities to record the performance of party school students with high scores. If the two examinations fail the examination, the system prompts that the party school students do not have the opportunity to take the examination and must study again.

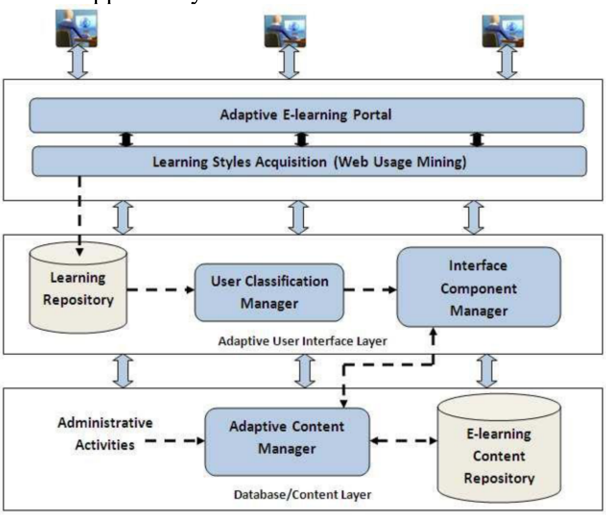

Fig. 3. Functional design

4.5 System test

Online video playback adopts high compression and low damage video format. Using HTML5 and embedded player video playback method, it can be cross-platform compatible with all current mainstream browsers, and solves the compatibility problem of online video playback. In appearance and layout on the other hand, it is realized through the responsive Bootstrap architecture. PCs, tablets and mobile phones can automatically adapt to improve the user experience. The reason why the system adopts the B/S architecture is that only Web programs need to be developed and installed on the Web server. To place the application, the client only needs to install a simple, universal and standard Web browser, which not only simplifies the maintenance work, but also reduces the maintenance cost.

5. Conclusion

The design and implementation of the NET model online party school highlights the informatization and digital advantages of college party organizations relying on campus networks to establish the educational management of college party schools. From the online party school structure to the functional design, simple and easy-to-use design principles are adopted, and the requirements for the implementation of software and hardware are relatively low. It breaks the limitations of time and space in the education of party schools in colleges and universities, effectively improves the efficiency and quality of party schools in colleges and universities, and promotes the development of informatization, digitization, science and modernization of college party school training.

This paper makes several notable contributions to the field of ideological and political education (IPE) in higher education. Firstly, it introduces a big data-driven model for IPE that leverages advanced technologies such as big data analytics and artificial intelligence to create a more scientific, precise, and personalized learning experience for students. Secondly, the authors develop an APH-based evaluation framework that enables systematic assessment of multi-dimensional learning outcomes in IPE, addressing a critical gap in the existing literature. Thirdly, they design and implement an integrated online platform that incorporates personalized content delivery, interactive simulations, and AI-driven feedback mechanisms, significantly enhancing the engagement and learning outcomes of students. Finally, through pilot studies conducted with a large sample of students, the authors validate the effectiveness of their model in fostering informed, ethically grounded digital citizens through technology-enhanced pedagogy. These contributions not only advance the theoretical understanding of IPE but also provide practical guidance for educators seeking to improve the quality and relevance of their teaching practices.

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Modern Management based on Big Data VI
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Research on the Problems and Countermeasures of Chinese Graduate Students' Time Management in the Digital Age

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Abstract. Time management ability is a ' compulsory course ' for postgraduate to enter the university campus. Especially in the era of highly developed information, the prevalence of digital communication methods and short videos makes the importance of time management ability more prominent in graduate students' completion of their studies and future career planning. And from the perspective of enterprises, enterprises also pay attention to the quality of human capital of graduate students. Therefore, this study used literature research method and questionnaire survey method to collect 215 questionnaires from February to March 2025. Using SPSS descriptive statistical analysis for data analysis, this paper discusses the difficulties faced by Chinese graduate students in time management in the digital age, and puts forward corresponding coping strategies on the basis of previous studies, aiming to provide reference for improving the comprehensive quality of graduate students and future career planning.

Keywords. The Digital Age; Graduate students; Time management

1. Introduction

University is the key stage of talent training. Students begin to engage with society and need career planning ability. Time management ability, as a core soft skill, directly affects academic efficiency and future competitiveness. However, most people do not realize the importance of time management.

At the same time, in the digital age, students are faced with challenges such as lack of self-control and academic procrastination. The temptation of games and short videos, the pressure of coursework examination papers, and the information anxiety brought by social media have all distracted their attention and time [1]. These problems are mostly caused by insufficient time management capabilities.

Based on this, this paper studies the current situation of graduate students ' time management ability in the digital era, in order to provide help for graduate students ' steady study, planning employment and future career development.

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2. Theoretical background

A number of individual-level studies have found that excessive Internet use is negatively correlated with college students ' time management disposition. While improving the convenience of information acquisition, we-media has also become a booster of the ' speed first ' culture [2]. In the study, Li Xueyan found that the detection rate of mobile phone dependence of postgraduates reached 38.29 %, with a relatively serious phenomenon of mobile phone dependence [3]. Zhang Yizhong and Chen Mengqi investigated the study time management of graduate students and found that graduate students have a strong concept of academic time, however, there are problems such as unreasonable time allocation, alienation of time use, and low time efficiency [4].

According to the Ministry of Education data, the number of college graduates in the 2024 session is expected to reach 11.79 million, an increase of 210,000 over the same period last year. The employment situation of graduates is still very complicated [5]. Senna 's research found that the input of extracurricular learning time has a positive impact on students ' knowledge acquisition, ability acquisition and value acquisition [6]. Wang Xing 's research found that college students ' internship experience plays a positive regulatory role in their career planning and employment quality [7]. The effective use of students ' spare time plays an important role in their personal development and is also an important part of obtaining employment competitiveness.

Li Pei pointed out that graduate students should form a correct time management attitude, strengthen self-awareness, establish long-term goals while strengthening self-control [8]. Only the time of ' now ' is the most valuable, and ' procrastination ' is the biggest obstacle to the individual 's grasp of ' now ' [9], postgraduates should consciously analyze the causes of procrastination and improve their personal mobility. Gan Liwen points out that colleges and universities can stimulate the internal driving force of graduate students by carrying out career planning, so that they can take the initiative to devote time to academic promotion and career preparation, and consciously do a good job in time management [10].

In view of the challenges brought by the digital age to graduate students ' time management, this study aims to investigate the specific difficulties of Chinese graduate students in time management, and on this basis to explore targeted and feasible research suggestions.

3. Methodology

As an information and data collection method, questionnaires are widely used in market research, social science, health research and education evaluation. In order to ensure the reliability and validity of the questionnaire, this study referred to a number of existing research projects and literature before designing the questionnaire, and conducted a pre-survey in the form of interviews to determine that Chinese college students generally have time management difficulties, and combined with the characteristics of college students in the digital age. A streamlined adjustment was made to ensure that it can accurately reflect the research topic. The questionnaire includes the following aspects:

- Procrastination behavior: The scale was used to evaluate the procrastination of college students in their studies, papers and examination reviews.

- Self-control and digital seduction: Design questions to assess college students ' resistance to digital entertainment (such as short videos, games, social platforms, etc.).
- Reading habits and time allocation: To investigate the reading time, reading content and time allocation of college students.
- Time management awareness and behavior: to evaluate college students ' cognition of time management and its implementation in actual behavior.

In addition, this study uses SPSS software to analyze the reliability of the questionnaire data. The results showed that the Cronbach 's α value was 0.86, indicating that the questionnaire had good internal consistency and reliable data quality.

This study uses online questionnaire survey to collect data through Credamo, an online questionnaire survey platform integrating questionnaire design, data collection and analysis, to explore the time management status of graduate students in the digital age. After the questionnaire design is completed, a unique questionnaire link is generated and sent to multiple postgraduate groups, including class groups, student union groups, and related academic forums, to ensure wide coverage of the questionnaire. After the questionnaire was distributed, a total of 220 answers were collected, and the response time of each answer was automatically recorded. According to the standard that the response time is less than 30 seconds, 5 invalid questionnaires were screened out, and 215 valid questionnaires were finally obtained, with an effective rate of 97 %. After the completion of the questionnaire, the data was imported into SPSS for descriptive statistical analysis to reveal the challenges faced by Chinese postgraduates in time management in the digital era.

4. Results

4.1. Analysis of the delay phenomenon of respondents

Procrastination is a common phenomenon, especially among college students. Wang Jiawei 's research shows that college students ' academic procrastination is positively predicted by mobile phone addiction [11]. The procrastination of college students will bring a series of adverse consequences [12], which will turn those important but not urgent events into important and urgent events, and bring great psychological pressure and time management dilemma to individuals.

As shown in Table 1, the phenomenon of procrastination among graduate students is more common. The specific performance is as follows: 81.66 % of the students rushed to complete 1-3 days before the deadline for homework, 60.53 % of the students rushed to piece together before the deadline for papers, and 75.45 % of the students did not review temporarily until one week before the final exam. The convenience of digital tools reduces the threshold of task initiation, but aggravates the psychology of procrastination, forming a vicious circle of ' task accumulation-pressure increase-inefficiency '.

Table 1. Statistics on respondents ' delays

Events	Proportion
Academic procrastination	81.66 %
Paper Procrastination	60.53 %
Exam review Procrastination	75.45 %

4.2. Analysis of respondents ' self-control

According to the questionnaire data in Figure 1, more than half of graduate students admit that it is difficult to resist the temptations in the digital environment. They are often addicted to browsing, likes and comments on social platforms, or addicted to online games and online shopping. At the same time, in the face of massive information, they are easy to lose their direction, their attention is frequently interrupted, and it is difficult to maintain self-control. This phenomenon causes time to be cut into a fragmented state, and the completion of learning and work tasks is significantly affected, further weakening the efficiency of time management.

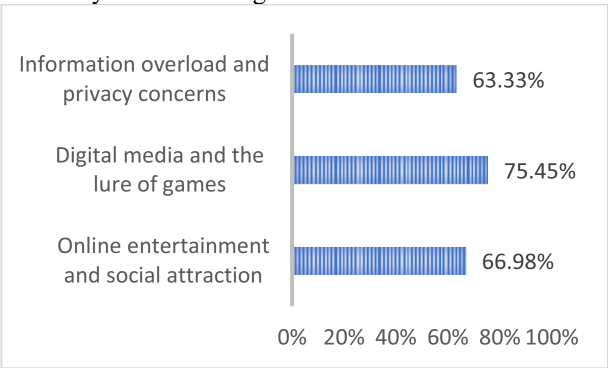

Figure 1. Statistics on the temptation of respondents to electronic devices

In general, in the digital age, graduate students face many temptations, including online entertainment and social networking (such as Weibo, WeChat, short video and online games), the attraction of digital devices, as well as information overload and privacy security challenges, affecting their learning and life.

4.3. Analysis of interviewees ' reading time

In the digital age, the importance of graduate students ' reading is more prominent. In the face of massive information and rapidly changing knowledge system, reading can help graduate students build critical thinking, improve information screening ability, and avoid being misled by false information. At the same time, in-depth reading of classics and professional books can consolidate the knowledge base, cultivate independent thinking and innovation ability, and lay a solid foundation for future career development and social participation. In addition, extensive reading also helps to enrich the spiritual world, improve humanistic quality, and maintain inner peace and depth in the fast-paced digital life. However, according to the 52nd ' China Internet Development Statistics Report ' released by the China Internet Network Information Center (CNNIC), as of December 2024, the number of Internet users in China was 1.108 billion, of which 1.105 billion were mobile Internet users, and the proportion of mobile Internet users reached 99.73 % [13].

As shown in the questionnaire data in Figure 2, the reading time of graduate students are obviously stratified, and a small number of students have a long reading time, showing the polarization of reading habits. Nearly half of the students read less than six hours a week, and the average reading time is less than one hour a day, reflecting multiple problems such as distraction, poor time management and academic pressure.

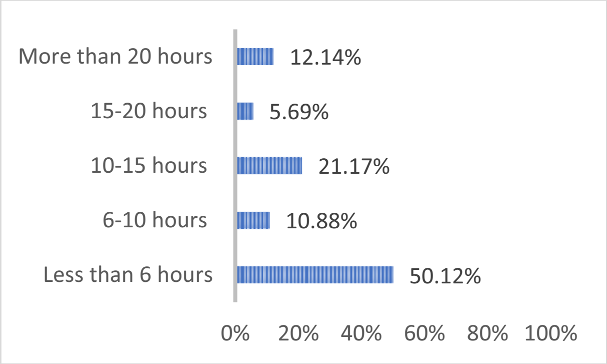

Figure 2. Respondents ' weekly reading time statistics of paper books

4.4. Analysis of the disconnection between management consciousness and management behavior of respondents

In the digital age, information overload and multiple choices make graduate students ' time management face unprecedented challenges. As shown in Figure 3, although 73.35 % of graduate students have time management awareness, only 21.65 % of them can transform this awareness into actual management behavior. This phenomenon of " disconnection between knowledge and action " shows that there is a significant separation between management consciousness and behavior. Many people have a clear understanding of time management in thought, but it is difficult to implement in action.

For example, some students said that due to the interference of the digital environment, fragmented information and instant satisfaction further weakened the action force; we often face complex tasks and multiple choices (such as whether to apply for a doctor or find a job, whether to participate in competitions, what tasks to complete today, etc.), often fall into decision-making difficulties, and the resulting management awareness is gradually weakened.

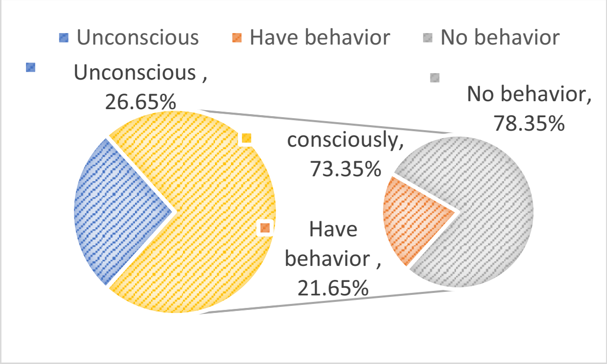

Figure 3. Statistics of respondents ' management consciousness and management behavior

5. Discussion

The above research shows that graduate students generally have problems such as academic procrastination, lack of self-control, differentiation of reading habits, and disconnection between management consciousness and behavior. The specific performance is as follows: Procrastination is common in the process of study, thesis writing and examination review; due to external interference such as online entertainment, self-control is weakened, resulting in confusion in time management and fragmentation of learning tasks; in addition, nearly half of the students read less than six hours a week, and their reading habits are significantly different. Based on the systematic review and in-depth analysis of relevant literature, this section will propose specific coping strategies for the above problems, aiming to effectively alleviate the challenges faced by graduate students in time management, improve their time planning and execution ability, and thus promote the development and improvement of their studies.

5.1. Stopping Procrastination and Starting with Microhabits

First, disassemble the task and reduce the difficulty. According to the theory of Vygotsky 's zone of proximal development, the stepwise decomposition of curriculum tasks and extracurricular expansion tasks can significantly reduce the psychological threshold of task execution. By deconstructing complex tasks into several stage sub-tasks, students can gain an immediate sense of achievement in the process of completing each sub-goal, thus improving learning motivation and task completion efficiency. This strategy can effectively reduce the fear and procrastination caused by the high difficulty of the task. Second, effective time management is essentially a dynamic resource allocation process based on individual physiological rhythms. By monitoring their own biological clock, students can accurately identify the daily cognitive peak period and arrange high-intensity learning tasks in the optimal efficiency range. At the same time, based on the principle of Gantt chart, the academic year goal is decomposed layer by layer into monthly, weekly and daily plans to form a visual task schedule, so as to clarify the time node constraint behavior and effectively suppress the procrastination tendency. Third, do a good job of psychological expectations and maintain a good psychological state. When the amount of learning tasks increases sharply or the difficulty exceeds expectations, individuals are prone to negative emotions such as anxiety and tension, which in turn triggers a vicious circle of procrastination. According to the stress coping theory, it is necessary to establish reasonable psychological expectations in the task planning stage, and formulate a flexible execution plan by pre-assessing the difficulty of the task and the length of time required. At the same time, it advocates strengthening psychological resilience through regular exercise, mindfulness meditation, etc., and building a positive emotional regulation mechanism. When emotional overload occurs, the pause mechanism should be activated in time to avoid the decrease of task execution efficiency due to emotional exhaustion [14].

5.2. Enhancing Self-Control and Optimizing Time Management

First, set time limits for the rational use of electronic devices and entertainment applications to avoid overindulgence. You can use specialized applications (such as Forest, RescueTime, etc.) to help control usage time. Cultivate self-discipline habits, such as setting fixed learning and rest time every day, keeping regular work and rest, and gradually improving self-control ability. Second, make a clear time management plan. Develop daily, weekly and monthly specific learning and life plans, set clear goals and tasks, and gradually complete them according to the plan. At the same time, time management tools can be used to record and track tasks to ensure that tasks are completed on time. Third, master the scientific time management method. Learn and practice scientific time management methods, such as tomato work method, every 25 minutes to concentrate on learning or rest for 5 minutes after work, improve concentration and work efficiency. Use the four-quadrant rule (emergency / important matrix) to classify and prioritize tasks, ensuring that important and urgent tasks are prioritized.[1]

5.3. Enriching Cognitive Approaches and Optimizing Game-Based Learning

To promote the ' micro-reading ' strategy, you can use fragmented time to read through the e-book App (such as professional literature abstracts), and gradually develop deep reading habits. Under the background of limited reading time of postgraduates, in addition to micro-reading, time management strategies can be integrated into cross-media learning, practical participation and mixed teaching to expand cognitive approaches and improve learning experience. In terms of cross-media learning, it is recommended that colleges and universities integrate time planning modules in the digital learning platform, guide students to develop personalized learning plans based on their own fragmented time, and improve the learning efficiency of scattered time. In terms of practical participation, graduate students should be guided to reasonably arrange their participation in academic activities and practical projects based on priority and time cost, and use time management tools to balance their studies and practices, so as to avoid the imbalance of time distribution and broaden their knowledge horizons. Under the blended teaching mode, through the combination of online and offline, students are guided to allocate learning time scientifically ; using virtual simulation technology and time challenge mechanism to strengthen time management awareness ; introduce game-based teaching elements, design time-limited interactive activities, stimulate learning enthusiasm, cultivate students ' ability to use time efficiently, and realize the diversification of cognitive approaches and the upgrading of learning experience.

5.4. Aligning Career Goals with Enhanced Time Management

Career planning in the digital age is not only the key to the future direction of graduate students, but also an important starting point for improving time management ability. Research shows that intrinsic motivation is the core driving force of efficient execution. [15]. Only when students truly understand their own needs and clarify their career direction, can they stimulate the internal driving force, effectively connect the management consciousness and management behavior, and realize the virtuous cycle of ' seeking something, doing something '.

At the school level, it is necessary to strengthen career planning guidance. The first is to clarify the key position of career planning guidance in talent training, integrate it into the whole process of postgraduate training, build a normalized system, cover the guidance objectives, contents, methods and assessment mechanism, and ensure the career development of students. The second is to build a three-level management structure of ' school employment guidance department-graduate school (or department) -department head ', integrate resources and promote collaboratively. The third is to give full play to the synergy between counselors and backbone teachers. Counselors conduct systematic guidance through entrance education. Backbone teachers carry out thematic guidance based on professional resources, integrate academic and professional needs, and help students clarify goals and optimize time management.

At the individual level of students, it is necessary to scientifically set the goal planning for graduate students. First establish the overall goal, sort out the tasks and achievements during the study period, and make it clear in the form of a list. Then clarify the time node, and accurately disassemble the time of each link according to the school 's training process and its own situation. Finally, the goal is refined into operational steps to promote the gradual realization of the goal and promote comprehensive development.

6. Conclusion

6.1. Research conclusion

This study combines the literature research method and the questionnaire survey method to reveal the severe situation of time management of Chinese graduate students in the digital era. The study found that graduate students generally have problems such as academic procrastination, lack of self-control, differentiation of reading habits, and disconnection between management awareness and behavior. The specific manifestations are as follows: procrastination is common in academic, thesis writing and examination review; due to the interference of online entertainment, self-control is reduced, resulting in time management out of control and fragmentation of learning and work; nearly half of the students read less than six hours a week, and their reading habits are obviously differentiated.

In view of the above problems, this study proposes a series of targeted coping strategies, including: through task decomposition, physiological rhythm planning and psychological adjustment to curb procrastination; by setting the time limit for the use of electronic equipment, formulating and implementing learning plans, and using scientific methods to cultivate self-control; increase the amount of reading by promoting ' micro-reading ' and cross-media learning. In addition, this study also emphasizes that schools should strengthen career planning guidance, and students should take the initiative to clarify the phased goals to achieve the connection between management awareness and management behavior. Through the collaborative efforts of universities and students, it is expected to significantly improve the time management ability of graduate students, and then promote their comprehensive quality improvement and career development.

6.2. Research insufficiency and prospect

Through the methods of literature research and questionnaire, this study makes a preliminary exploration on the current situation of time management of postgraduates, reveals the existing problems and causes, and puts forward improvement strategies. However, the research still has the following limitations, which need to be further improved in the future:

- The scope of the survey is limited: the research does not cover the postgraduate groups of different types of universities in China, the sample representation is insufficient, and the universality of the survey results needs to be verified.
- The survey tools need to be optimized: the questionnaire design refers to the authoritative theory, however the uniqueness of the way and content of the question is insufficient, which needs to be further improved.

- Insufficient depth of data analysis: only the results of the questionnaire were collated and summarized, and qualitative analysis tools were not used to explore the data in depth.

In summary, in the future research, it is necessary to continue to improve, expand the scope of the survey and the number of samples, enhance the representativeness of the samples, improve the survey tools, learn to use a variety of data analysis tools, enrich the research content, and gradually improve the research results.

6.3. Future research direction

Future research can pay more attention to the differences in time management among postgraduates of different disciplines and grades, such as the differences in time allocation and learning habits between science and engineering postgraduates and humanities and social sciences postgraduates. At the same time, we can further explore the influence mechanism of digital tools (such as time management App and online learning platform) on graduate students ' time management, and examine their use effect, potential problems and optimization strategies. In addition, the study can also explore the impact of cultural factors, social environment and mental health on graduate students ' time management, and try to build a more comprehensive and refined time management intervention model. Finally, longitudinal research methods can also be used to track the time management status of graduate students at different stages and their impact on academic achievement and career development, so as to provide longer-term and dynamic support for graduate students ' time management.

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Appendix

Postgraduate time management status questionnaire

Dear classmates.

Hello! Thank you very much for taking the valuable time to participate in this questionnaire survey. We are conducting a survey on the current situation of postgraduate time management, and we need your help. This survey is conducted anonymously, and participation is voluntary with the right to withdraw at any time without penalty. The results are only used for academic research purposes. Your answer is no right or wrong. Please choose according to the actual situation, please ensure that no items are missing. Thank you again for your cooperation and support!

1. Your gender
   A male   B female
2. Your grade
   A Postgraduate Year 1   B Postgraduate Year 2   C Postgraduate Year 3
3. Which of the following situations do you have in terms of procrastination (multiple choice)
   A Academic Procrastination (1-3 days before the homework deadline)
   B Paper Procrastination (hurriedly pieced together before the deadline)
   C Exam review Procrastination (review began one week before the final exam)
4. When you use electronic equipment, which of the following situations exists (multiple choice)
   A Often distracted in learning, opening short video software and shopping software.
   B It is difficult to resist the temptation of digital media such as online games and TV series.
   C When faced with a large amount of information, we are often confused by information overload.
5. Your weekly reading time is
   A Less than 6 hours
   B 6-10 hours
   C 10-15 hours
   D 15-20 hours
   E More than 20 hours
6. Which of the following situations do you have in terms of time management awareness (multiple choice)
   A I think time management is very important to academic success
   B I have a clear time management goal
   C I will use the schedule or schedule to arrange my tasks
   D I often plan my study time in advance
   E I often evaluate my time use
7. Which of the following situations do you have in your time management behavior (multiple choice)
   A I often complete the task as planned
   B I can effectively use fragmented time (such as waiting time) to learn
   C I can effectively decompose tasks into manageable small tasks
   D When time management is difficult, I will adjust my plan
   E I can stay focused, not easily distracted

   Thank you again for your cooperation! I wish you a smooth study and a happy life!

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Research on Hunan's Practice of Synergistic Empowerment of Urban Learning Community Construction by "Three Types of Education" in the Digital Intelligence Era

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Abstract: Against the backdrop of the deep integration of the concept of lifelong education and digital intelligence technology, the synergy of higher education, vocational education, and continuing education (referred to as "three types of education(3ToE)") has become the core path to promote the construction of learning communities in Hunan's cities. This paper, based on Hunan's strategic positioning of "three highs and four news", analyzes the regional characteristics and practical challenges of the "3ToE" synergy in empowering community education, and proposes to take digital technology as the engine, through mechanism innovation, resource matching, scenario deepening, and ecological co-construction, to build a lifelong learning service system with Hunan characteristics. The research, combined with the practices in Changsha, Zhuzhou and other places, verifies the effectiveness of the "3ToE" synergy in solving the mismatch of community education resources and enhancing residents' digital literacy, providing references for the construction of a learning society.

Keywords: Digital intelligence era; Synergy of three types of education; Lifelong education; Learning community; Practice in Hunan

1. Introduction

With the rapid development of new-generation information technologies such as artificial intelligence, big data and blockchain, human society is accelerating its entry into the digital and intelligent era. Digital and intelligent technologies have permeated every aspect of social life to an unprecedented depth and breadth, bringing brand-new development opportunities to education, driving profound changes in the educational ecosystem, and providing strong technical support for building a learning society where all people pursue lifelong learning. As the important component and basic unit of the learning society, the learning community is the key carrier of lifelong learning concept. In the age of wisdom, the construction of a learning community is facing the urgent

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need to transform from traditional mode to digitization, personalization and ultimate transformation. By analyzing the needs of the residents to learn the needs of the residents, and providing the custom chemical acquisition service, the construction level and the service efficiency of the learning community are improved. The collaborative development of education, vocational education, and continued education is the key path of building a lifelong learning system, and in the context of the wise age, it is of great practical significance to promote the construction of the "three types of education(3ToE)" collaborative urban learning community.

With the proposal of "Building an education system that serves lifelong learning for all" in the "14th Five-Year Plan for Education Development in Hunan Province", Hunan is confronted with multiple development tasks: First, it needs to enhance the vocational skills of new urban residents in order to accommodate the industrial transfer from the Yangtze River Delta. Second, it must strengthen digital education for the elderly in response to the aging population (with those aged 60 and above accounting for 21.87%). Third, it is necessary to break down the barriers of regional educational resources in promoting the integration of Changsha, Zhuzhou and Xiangtan. The synergy of higher education, vocational education and continuing education, through knowledge spillover, skill transformation and local services, has become a key approach to addressing "urban diseases" and building resilient communities.

Hunan Province has 54 undergraduate universities and 86 vocational colleges. Hunan Open University has 20 municipal and prefectural (industry) colleges and 131 county-level learning centers. The density of educational resources in Hunan ranks among the top in central China. Currently, there are a total of 14 community universities, 65 community colleges, 708 community schools, and 2,785 community school service-learning centers in the province. Four national community education demonstration zones, eight national community education experimental zones, and sixteen provincial community education experimental zones have been established in Hunan. However, there are still problems such as scattered "3ToE" resources and lagging digitalization of community education. This article focuses on how "3ToE" can achieve precise supply and demand matching through digital and intelligent technologies, providing a "Hunan model" for the construction of learning communities in central provinces.

2. Method

This study comprehensively employs multiple research methods. The first is the literature research method, which sorts out the relevant theories and practical achievements at home and abroad regarding educational transformation in the digital intelligence era, the synergy of "3ToE" (S3ToE), and the construction of learning communities, grasping the research dynamics and cutting-edge trends, and providing a solid theoretical foundation for this research. The second method is the case analysis method. By selecting representative cases of urban learning communities in regions such as the Changsha-Zhuzhou-Xiangtan metropolitan area, northern Hunan, southern Hunan and western Hunan, it deeply analyzes their practical experiences and existing problems in the coordination of "3ToE" and digital intelligence empowerment, summarizes successful models and lessons learned from failures, and provides practical basis for proposing targeted countermeasures in the future.

3. Literature Review

In the era of digital intelligence, research on the coordinated development of higher education (HE), vocational education (VE) and continuing education (CE) and the construction of a learning society shows a multi-dimensional exploration trend.

3.1 Policy Orientation and Strategic Positioning

The report of the 20th National Congress of the Communist Party of China proposed "coordinating the collaborative innovation of vocational education, higher education and continuing education" [1], and the Third Plenary Session of the 20th Central Committee further emphasized "promoting the digitalization of education to empower the construction of a learning society" [2]. Coordinating the collaborative innovation of vocational education, higher education and continuing education is conducive to promoting the organic connection between the education chain, talent chain and industrial chain, innovation chain, and providing intellectual support for the progress of social productive forces and the construction of a learning society [3]. Based on the coordinated innovation of the three types of education, we should enhance the innovation capacity through the digitalization of education, deepen the collaborative innovation among different types of education through digital technology innovation, and promote the construction of a learning society by strengthening lifelong learning and lifelong education [4]. Yunnan, Henan and other places have established a collaborative mechanism of "3ToE", integrating resources of open education, vocational education and continuing education to serve lifelong learning for all [5]-[6].

3.2 Practice Path and Model Innovation

In terms of collaborative mechanisms and platform construction, credit recognition and qualification framework, international experience shows that agreement endorsement, connection and integration, parallel dual-track, and convergence and integration are the main models of the "3ToE" collaboration [7]-[8]. In China, the certification of learning outcomes is promoted through the construction of credit banks. For instance, Guangdong Open University has established a physical center for a lifelong education credit bank, enabling 114 institutions to participate and 1.39 million lifelong learning accounts to store outcomes [9]. Jiangsu University of Technology integrates the resources of "3ToE" through the discipline management mechanism to promote interdisciplinary innovation [10]; The integration of industry and education as well as the convergence of science and education, Guangdong Polytechnic of Science and Technology has relied on enterprises such as Huawei and Chinasoft to jointly build a hybrid cloud platform, achieving the integration of scientific research, teaching and practical training. Jiangsu Polytechnic of Architecture has enhanced teaching effectiveness by empowering course development with AI, constructing a "learning menu" and virtual simulation platform [9]-[10]. Regional collaboration and group-based education: The Guangdong-Hong Kong-Macao Greater Bay Area explores cross-regional collaboration, such as the cooperation between Guangdong Open University and Macao's universities to jointly build the qualification standards for the elderly care service industry [9]; Beichuan Qiang Autonomous County has optimized the allocation of educational resources between urban and rural areas through the "high-quality schools + weak schools" group model [11].

In terms of the strategies for building a learning society and the digital learning ecosystem, Beijing, Jiangsu and other places have narrowed the educational gap through models such as "smart classrooms" and "dual-teacher teaching". For instance, Xiongan Shijia Hutong Primary School has utilized 5G and AI technologies to achieve synchronous teaching between Beijing and Xiongan [12]. Hubei Polytechnic College has proposed to establish a "3ToEching" collaborative digital alliance. Promote the digital credit system and qualification certificates [13]. Fusui High School has collaborated with Chengdu No. 7 High School to implement the "dual-teacher Classroom", achieving synchronous teaching and resource sharing across different locations [14].

In terms of citizen participation and lifelong learning, Hunan Province has built a lifelong learning network through community education centers, farmers' cultural and technical schools, etc., covering both urban and rural residents [15]. The Ministry of Education emphasizes promoting a lifelong learning system covering all citizens with fairness, innovation and digitalization at its core [16]. The comparison of the "3ToE" collaborative model is shown in Table 1.

Table 1. Comparison Table of the "3ToE" Collaborative Model

Collaboration Model	Characteristics	Typical Cases
Credit Recognition and Qualification Framework	Realize the certification and conversion of learning achievements	Lifelong Education Credit Bank of Guangdong Open University
Industry - Education Integration and Science - Education Integration	Co - build platforms with enterprises, integrate scientific research and teaching resources	Hybrid Cloud Platform Co - built by Guangdong Polytechnic of Science and Technology and Huawei
Regional Collaboration and Group - based School - running	Optimize regional resource allocation, promote cross - regional collaboration	Cross - regional qualification standard co - construction in the Guangdong - Hong Kong - Macao Greater Bay Area

3.3 Technology Empowerment and Educational Transformation

3.3.1 Application of Digital Intelligence Technology

(1) Innovation of teaching mode Xi 'an Jiaotong University has implemented the "Seven Major Projects" of AI+, namely, majors, courses, teaching, learning, evaluation, resources and platforms. It aims to build problem graphs, knowledge graphs and ability graphs for the future, and conducts exploration and practice throughout the entire process and chain, including educational concepts, teaching methods and training models, with the goal of cultivating top-notch innovative talents needed for future social development [17]. Fusui High School has collaborated with Chengdu No. 7 High School to implement the "dual-teacher Classroom", achieving synchronous teaching and resource sharing across different locations [14].

(2) Resource integration and personalized Learning: Jiangsu College of Architecture and Technology has developed a "granular" teaching resource library and virtual simulation platform to meet the needs of fragmented learning [12]; Beijing provides multi-scenario learning services through the "Citizen Smart Learning Experience Center" [18].

3.3.2 Data Governance and Quality Assurance

(1) Data-driven decision-making: Henan Open University optimizes the allocation of educational resources through data governance, promoting teaching reform and school governance [6]; Guangdong Open University uses credit bank data to evaluate the conversion effect of learning outcomes [9].
(2) Quality Standards and Certification: The European Union has established a quality assurance mechanism through the European Qualifications Framework. Domestic scholars suggest improving the national qualifications framework and the credit bank system, and strengthening the quality certification of the "3ToE" collaboration [8].

4. Result

The empowerment of digital intelligence for the collaboration among the three types of education is not only an inevitable requirement for accelerating the construction of a learning society, but also an innovative measure to promote the high-quality development of vocational education, higher education and continuing education themselves. The model of digital intelligence empowering the collaboration among the three types of education is shown in Figure 1, where HVE represents higher vocational education, HCE represents higher continuing education and VCE represents vocational continuing education.[19]

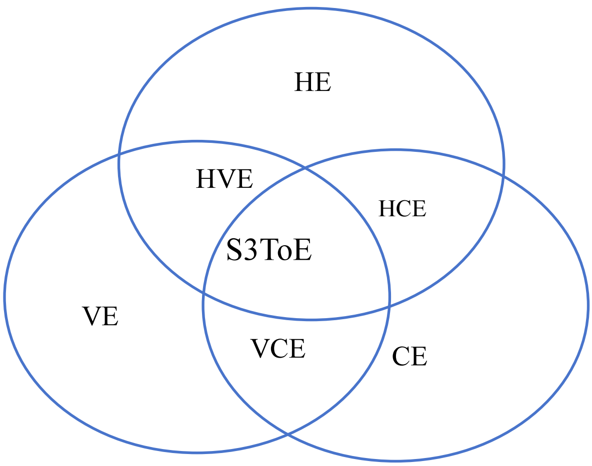

Figure 1. The model of S3ToE empowered by digital intelligence

4.1 Establish a collaborative mechanism of "provincial-level overall planning - regional coordination - industrial coupling"

(1) Top-level Design: Establishing a "Three-Party Collaboration" Policy Toolkit
The "Hunan Province Lifelong Education Promotion Regulations" was promulgated, clearly stipulating that universities should open no less than 30% of their high-quality course resources to communities each year. Vocational colleges should develop "community skills packages" in line with the leading industries of prefecture-level

cities and prefecture-level cities, such as "Automobile and Electrical Engineering" courses in Xiangtan and "Nonferrous Metal Processing" courses in Chenzhou.

The "Longzhuzhongtan Three-Party Collaboration" joint meeting system was established to promote the inter-library borrowing and sharing among universities in the three regions, vocational schools' training bases, and community learning centers. For instance, the metallurgical laboratory of Central South University opened virtual simulation experiments to industrial workers in Qingshitang Community in Zhuzhou.

(2) Organizational Innovation: Establishing the "Industrial College in Community" Model

Based on the "Top Ten Industrial Clusters" in Hunan Province, set up "Micro Industrial Colleges" in communities: For instance, in the community of Changsha Economic Development Zone, three companies jointly established a "Specialized Class for Intelligent Maintenance of Construction Machinery" and adopted a tripartite collaboration model of "professors from universities explaining theories + engineers from enterprises guiding practical operations + providing venues by the community".

Develop the "Matrix of Huaxiang Characteristic Courses", including:

Red Culture Category: Collaborate with Shaoshan Cadre College and university Marxist colleges to develop the "Mobile Party Lecture" VR course, covering 100 red communities across the province.

Intangible Cultural Heritage Inheritance Category: Hunan Institute of Fine Arts and Liling Ceramic Community jointly establish a "Underglaze Color Craft Skills" digital workshop, achieving modern transformation of traditional craftsmanship through 3D printing technology.

(3) Technology Empowerment: Build the Integrated Digital Platform of "Xiangxue Tong"

Integrate the resources of "three types of education" across the province, construct a framework of "1 (provincial platform) + 14 (municipal and prefectural sub-platforms) + N (community terminals)", connect with the "My Hunan" government affairs cloud, and enable "one-click ordering" of learning demands and "intelligent delivery" of course resources.

Utilize blockchain technology to establish the "Xiangxue Points" system. Residents' points earned from MOOC learning at universities, vocational school skills training, and community volunteer services can be exchanged for academic qualification improvement vouchers, scenic area tickets, etc., enhancing participation stickiness.

4.2 Build a resource supply system that is "demand-oriented + regionally distinctive"

4.2.1 Stratified and Categorized Development of Curriculum Resources

(1) Newcomers: For the migrant workers who have moved to Changsha from other places, develop a curriculum package titled "Digital Skills + Urban Integration", including modules such as "Use of Smart Terminals", "Interpretation of the Labor Contract Law", and "Dialect Culture of Changsha, Zhuzhou, and Tanjiang";

(2) Elderly: Collaborate with Hunan University of Chinese Medicine and the Provincial Association for Elderly Health Care to launch the "Xiang-style Health Care" series of courses, covering topics such as "Production of Traditional Chinese Medicine Diet", "Arrangement of Square Dance (with elements of Hunan folk songs)", and "Operation of the 'Xiang Tax Connect' APP";

(3) Teenagers: Universities provide online live broadcasts of "Yuelu Science and Innovation Lecture Hall", vocational schools open offline experiences of "Intelligent Manufacturing Workshop", and communities organize "Little Engineers" competitions, forming a closed loop of "Theory - Practice - Innovation".

4.2.2 Construct a "Virtual-Real Fusion" Learning Environment

(1) Offline Scenario: Build "Smart Maritime Learning Stations" in communities of cities along the Yangtze River such as Changde and Yueyang, connect with the ship simulation system of Hunan Transportation Vocational College, and provide opportunities for port workers to enhance their digital operation skills;
(2) Online Scenario: Develop a VR cooking class for "Xiang Cuisine Masters", allowing users to sense oil temperature and knife skills through smart wristbands. Upon course completion, it can be certified by the Hunan Catering Industry Association.

4.2.3 Establish a dynamic adjustment mechanism for resources based on "two-way feedback"

Collect learning demands through community intelligent terminals and grid workers' visits every quarter. Utilize natural language processing technology to analyze frequent words and guide universities and vocational schools to adjust course offerings.

Introduce third-party evaluation institutions and incorporate class attendance rates and career conversion rates into the resource allocation model. Eliminate inefficient courses.

4.3 Innovation: "Domestic Cultivation + Flexible Mobility" Model for Teacher Recruitment and Training

4.3.1 Establish a "Library of Mentors for Three Schools of Thought in Huxiang"

Classify and include three types of teachers: "Silver-haired Professors" from universities, "Skill Masters" from vocational schools, and "Eminent Individuals" from communities.

Implement the "Flexible Teaching System", allowing teachers to accept orders online through the "Xiangxue Tong" platform. The teaching hours can be converted into social service credits for university teachers and enterprise practice hours for vocational school teachers.

4.3.2 Implement the "Dual-Teacher Empowerment" Special Plan

(1) Enhancement of Digital Competence: Relying on the Smart Education Research Center, 1,000 community teachers will be trained annually. They will focus on mastering skills such as AI course design and learning data analysis. Those who pass the assessment will be awarded the "Hunan Digital Mentor" certification.
(2) Strengthening Local Practical Competence: Organize university teachers to participate in the "Community Fieldwork Program", requiring each person to stay in a community for no less than 2 weeks each year and produce 1 teaching case with Hunan

flavor. For example, develop an "English for Tourist Service in Scenic Areas" course by integrating the tourism industry of Zhangjiajie.

4.3.3 Improve Incentive Mechanism and Career Development Pathways

Establish the "Special Allowance for Community Education in Hunan Province", providing a certain subsidy per class hour to teachers involved in the "3ToE" collaboration, and giving priority to recommending them for provincial-level teaching achievements awards.

Open up the channels for professional title evaluation for community teachers and school teachers, allowing community education work experience, course development achievements, etc. to be converted into teaching workload equivalently, thereby enhancing career attractiveness.

4.4 Deepening the Integration and Innovation of "Community Governance + Lifelong Learning"

4.4.1 Incorporating the Construction of Learning Communities into Urban Renewal

In the renovation of old residential areas in Changsha, a "15-minute Smart Learning Circle" was concurrently constructed. For instance, the Chaozhong Street Community in Kaifeng District transformed an old building into the "Hunan Provincial Intangible Cultural Heritage Learning Hall", integrating the digital resources of Hunan Institute of Fine Arts to achieve the combination of cultural inheritance and community building.

4.4.2 Develop the "Community Governance Minor Program"

Collaborating with public administration colleges of universities and property management majors of vocational schools to cultivate "Building Residents' Representatives" and "Members of the Owners' Committee", the courses include "Formulating the Owners' Covenant", "Operation of the Smart Community Platform", etc.

4.4.3 Innovation: "Learning Points + Community Service" Linkage Mechanism

Residents can exchange their "Xiangxue Points" accumulated through learning for community services, such as free use of the community shared kitchen and priority participation in cultural activity registration. At the same time, the volunteer service hours will be rebalanced as learning points, forming a "Learning - Service - Learning" virtuous cycle.

In the community of Jiuhua Economic Development Zone in Xiangtan, the "Skill Exchange" program was piloted. Industrial workers could obtain points by teaching "CNC Lathe Operation", which could be exchanged for after-school tutoring for their children and elderly care courses, promoting the redistribution of community resources.

4.4.4 Cultivating "Self-Organizing" Learning Communities

Support the establishment of "learning autonomous groups" within communities. For instance, the "Craftsmen Learning Society" was spontaneously organized by retired engineers to develop practical courses such as "Maintenance of Household Electrical Circuits" and "Renovation of Old Household Appliances". The government provides equipment subsidies and online promotion.

Organize a series of activities under the theme of "Hunan Learning Festival", including the "Community Skills Competition" in Changsha, the "Senior Digital Talent Show" in Yueyang, and the "Newcomer Entrepreneurship Sharing Conference" in Chenzhou. This aims to create a learning atmosphere for all citizens.

5. Conclusion

The practice of the "3ToE" collaborative empowerment of a learning-oriented community in Hunan Province indicates that regional characteristics constitute the core competitiveness, digital and intelligent technologies act as catalysts, and mechanism innovation serves as a breakthrough point. By aligning with the "Three Highs and Four New" strategies, converting the demands of industries such as construction machinery, tourism, culture, and health care into community education content, and leveraging technologies like blockchain and VR to address resource mismatches, the precision and effectiveness of lifelong education services can be effectively enhanced.

Accelerate the formulation of the "Regulations on Lifelong Education Promotion of Hunan Province", set aside a special fund, and promote the legalization and normalization of the "3ToE" collaboration. In the industrial clusters such as the green chemical industry in Yueyang and the non-ferrous metals industry in Chenzhou, pilot projects of "Community Industrial Colleges" have been carried out to achieve the goal of "admission means recruitment, classes mean on-the-job training, and graduation means employment". Based on the Maolanshan Video Cultural and Creative Park, developing the "Virtual Community University" metaverse platform, create scenarios such as "Immersive Red Education" and "Virtual Skill Training", and expand the coverage of high-quality resources. Build the "Xiangxue" series of community education brands, such as "Xiangcai Master Classroom", "Xiangnu Domestic Service College", and "Xiangye Craftsmen Workshop", to form a distinctive Hunan model. The construction of learning communities in the digital and intelligent era is essentially driven by educational form innovation to upgrade urban governance. Hunan should continue to leverage its advantages of abundant "three types of education" resources and distinctive industrial characteristics, making lifelong learning an endogenous driving force for urban development, and providing replicable "education-strong province" construction experiences for the central region and the whole country.

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Design and Evaluation of an Intelligent Teaching Platform Integrating Virtual Reality and Large Model Technologies

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Abstract. This study designs an advanced teaching platform and assess its effectiveness using a new evaluation system. The study constructs a framework for an experimental teaching intelligence platform based on VR Large Model technology. The framework includes six parts: presentation, skill, function, application, technology, and infrastructure. This research also proposes a new teaching evaluation system. This system integrates students, teachers, and enterprises as the three core evaluation subjects. It also improves students' learning ability, and optimizes their learning process. The systematic enhancement and promotion of this platform offer valuable insights for effectively advancing learning and teaching quality in China.

Keywords. VR, Large Model, Experimental Teaching, Intelligent Platform

1. Introduction

In the era of rapid globalization and digitization, the field of education faces unprecedented challenges and opportunities. For most learners, the traditional education model has issues such as a monotonous learning experience and an inability to effectively stimulate interest and initiative in learning. The teaching model designed for the intelligent experimental teaching platform built upon the VR large model technology is precisely developed to address these issues. New technologies and platforms such as virtual reality (VR), artificial intelligence, and intelligent education provide efficient and convenient teaching means and tools for teaching model reform. Based on advanced technologies and combined with high quality teaching staff, the new teaching model helps guide and innovate teaching concepts.

Scholars have begun to explore how to combine VR technology with theory to design an experimental teaching programme that can arouse students' interest and improve their learning efficiency. Sholihin Mahfud (2020) explored the design of a virtual experimental platform for economics and management [1]. Manuel Brunner et al. (2020) utilized VR-related technologies to study the relationships between producers and customers, successfully retaining existing customers and identifying potential ones [2].

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In recent years, AI has been widely used in the field of education, highlighting the great potential it holds. Nauman Khan et al. found that interest in academic research increased explosively after ChatGPT emerged [3]. Georgios Lampropoulos of the Department of Applied Informatics, Faculty of Information Sciences, University of Macedonia, provided an overview and mapping of the existing literature on the convergence of AI with VR and AR technologies. The reviews indicated the future directions of AI research [4]. Ikpe Justice Akpan et al. of Kent State University, Kent, Ohio, USA, investigated emerging conversational and generative AI (CGAI/GenAI) and human-like chatting bots [5]. Henriikka Vartiainen of the University of Eastern Finland revealed how design ideas for concrete digital artifacts emerge in the ongoing relationship between human and non-human actors [6]. Anass Bayaga from the University of the Western Cape explored the role of AI on the behavioural intentions and practical use of educators and students, emphasizing the importance of the theory of technology adoption in user perception and ease of use [7]. Eduardo Lérias assessed the AI literacy of teachers at PPU and argued that it is desirable to implement strategies to develop teachers' competence in teaching with AI [8].

2. Design and Evaluation of an Intelligent Teaching Platform Integrating Virtual Reality and Large Model Technologies

The intelligent teaching platform for experimental teaching based on VR Large Model technology consists of six aspects: presentation, skill, functional, application, technical, and infrastructure layers. It is designed base on an existing model. Users can flexibly utilize virtual learning spaces combined with AI through the intelligent teaching platform. The design of the platform system framework is shown in Figure 1.

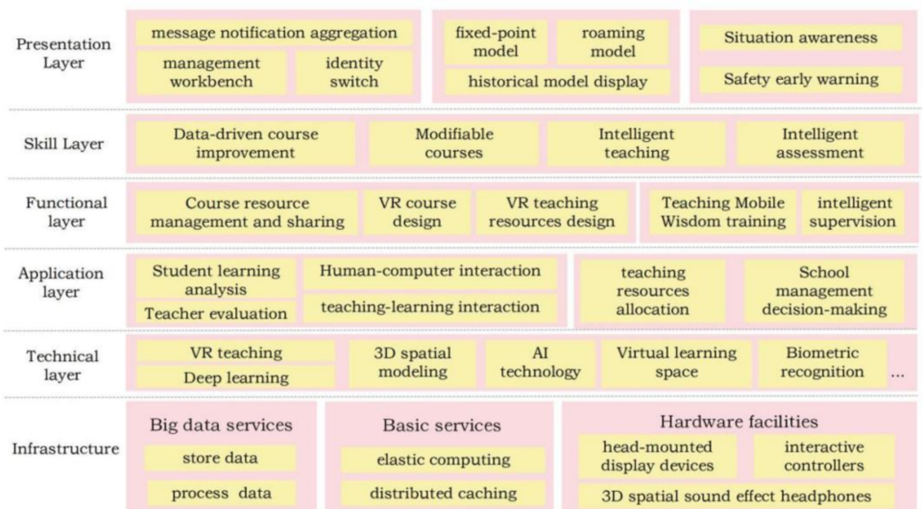

Figure 1. "AI+Virtual Learning Space" Smart Teaching Platform System Framework Design

Presentation Layer. The presentation layer is mainly responsible for presenting visualized interfaces and information to users, while realizing the display and use of the VR model of the platform at the same time. The former consists of a management workbench, identity switch, message notification aggregation, etc., and the latter includes a fixed-point model, roaming model, and historical model display. In terms of platform interface information, users can choose a specific usage mode by switching their self-identity after logging in. The VR model of the platform contains three more specific models. The fixed-point one is the basic model for a specific situation designed by the virtual learning space designer. Designers will not change its data within a short period of time. It is usually used for setting the overall environment of the situation. It has a smaller amount of data storage and occupies less storage space. The roaming model captures data freely and in real-time. It will detect elements within the specified virtual scenario environment on a three-day cycle, capture changing elements that significantly impact the simulated scenario. Then it will make modifications based on the fixed-point model to ensure the virtual environment better aligns with reality. The combination of the fixed-point and roaming model is conducive to the efficient and rapid construction of learning scenarios that fit the actual problem.

Skill Layer. The skill layer embodies the technology that integrates the smart teaching platform with AI technology to achieve relevant goals. Personalized learning will customize learning paths for students based on their specific performance and proficiency in applying knowledge. Modifiable courses include course production skills and technical application skills. The platform needs to ensure that the VR courses can be re-edited to guarantee the timeliness and advancement of VR teaching. Intelligent teaching uses AI virtual teachers to assist human teachers in teaching activities. It will analyze the students' learning performance during each period of time. Based on the feedback, it can provide the key points for the human teachers' tutoring. In this way, the smart teaching platform can improve the teaching efficiency through the mode of "consolidation by AI teachers + reinforcement of weaknesses by human teachers". Data-driven course improvement provides the necessary data to optimize the further courses. Intelligent assessment evaluates the learning effect of students and the teaching effect of teachers, promoting subsequent enhancements.

Functional layer. The functional layer focuses on the function of the teaching platform. AI technology can manage and share teaching resources by uploading course resources to the intelligent cloud platform of the public education system. VR course design includes learner characteristics and learning content analysis, ensuring teaching objectives, teaching media selection, etc. It can guide teachers in curriculum design while coordinating the overall course schedules of each user through algorithms. Furthermore, VR teaching resources design is an in-depth design of existing and planned research. It concludes elements like design principles, basis, objectives, and so on. Teaching mobile intelligent training and supervision ensures the teaching quality.

Application layer. The application layer is the specific application of the functional layer in educational scenarios. Student learning analysis can reliably intervene and correct students' behaviours while dissecting their learning situations and providing corresponding teaching resources. Human-computer interaction and teaching-learning interaction follow the application process of "multi-party information input through multiple channels, cross-analysis of information, result feedback and adjustment, and accurate information output". This process help achieve the purpose of information exchange and teaching training between human and computer, as well as teachers and learners. Teacher evaluation assesses teachers teaching behaviours. It will record and archive classroom teaching irregularly, and rate the classroom teaching content, teaching methods and classroom interactions.

Technical layer. The technical layer is composed of technologies that support the realization of platform functions. Based on the developments of VR models, VR teaching and the construction of VR models are the basis of VR immersive teaching. It provides a real-like situational environment for virtual VR immersive teaching to ensure the smooth progress of the courses. Real-time 3D spatial modelling platforms represented by Unity 3D facilitate the realization of immersive virtual environments. AI technology provides computing power for programs such as behavior decoding and element analysis. The virtual learning space ensures that learners can carry out learning and practice in a virtual space that is as close as possible to the real situation. Additionally, deep learning is utilized for training teaching models and mining user data. Computer vision is also employed for designing the platform interface and processing images. UI is a significant part of it which can design the layout, color, images, and so on. An excellent UI design can enhance users' usage experience and increase the value of the platform.

Infrastructure. Infrastructure provides the basic services and supporting environment for the platform operation. Big data services store and further process the collected data. Basic services such as elastic computing and distributed caching ensure the platform's basic operation. Hardware facilities such as head-mounted display devices, interactive controllers, and 3D spatial sound effect headphones ensure the feasibility and teaching quality of VR teaching. The basic services cover computing, storage, networking, backup, and security, ensuring the platform's operation.

In the overall structure of this platform, the infrastructure layer provides underlying hardware support for the technology layer. The application layer supplies relevant data and corresponding application scenarios for the functional layer. The functional layer offers teaching resources and functional support for the skills layer. The skills layer provides specific content and achievements for the presentation layer, and the presentation layer feeds back the current status of the platform and excavates more demands and information.

3. A diversified and multi-dimensional teaching evaluation system

The teaching evaluation system with diversified evaluation subjects, methods, and dimensions can provide a continuous driving force for developing economics and management courses with the theory-reality-virtuality trinity teaching mode (see Figure 2). The theory-reality-virtuality trinity teaching model integrates theoretical knowledge learning, practical project operations, and virtual simulation exercises. It evaluates from multiple subjects and diagnoses teaching from multiple dimensions to construct a big - data - based teaching evaluation system, thereby promoting the cyclic improvement of teaching processes. The newly constructed theory-reality-virtuality trinity teaching model of economics and management courses is the basis of this project. The established evaluation system is shown in Figure 2.

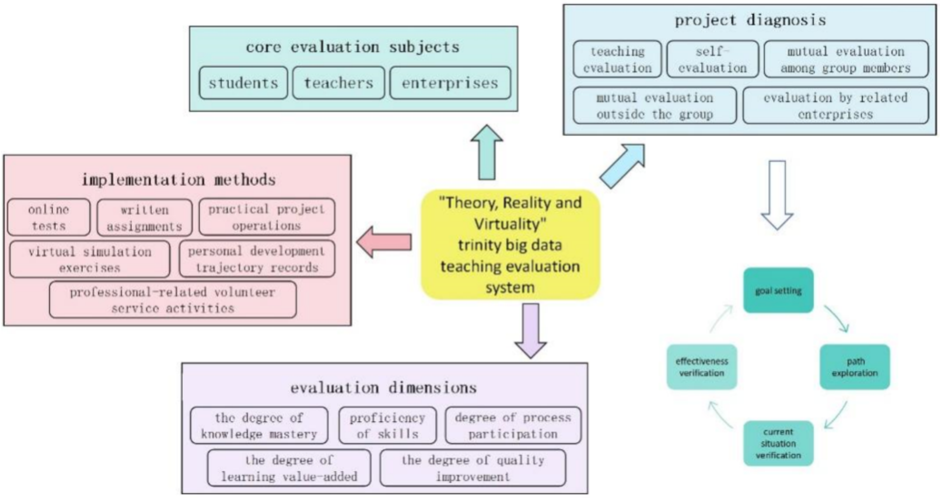

Figure 2. Theory-Reality-Virtuality Trinity Large Data Teaching Evaluation System

In specific practice, this system integrates students, teachers, and enterprises as the three core evaluation subjects and jointly participates in project diagnosis and improvement through teacher evaluation, student self-evaluation, intra-group and inter-group peer evaluation, and evaluation by related enterprises. It promotes the closed-loop evaluation process of "goal setting—path exploration—current situation verification—effectiveness verification" and ensures continuous improvement and reflective practice.

In terms of evaluation dimensions, researchers subdivide this system into five major dimensions: knowledge mastery, skill proficiency, process participation, quality improvement, and the degree of learning value-added. Emphasis is placed on assessing students' comprehensive ability to solve real-world problems, aiming to drive a leap in students' learning outcomes. In implementation methods, multiple strategies have been adopted: online tests, written assignments, and so on. Researchers also use real project operations and virtual simulation exercises to precisely detect the level of students' knowledge mastery. High score in this aspect indicates better knowledge grasp. The system evaluates the skill proficiency of students is mainly based on their performance of practical project operations and virtual simulation exercises. This system judges the process participation from personal development trajectory records and participation in practical projects, volunteer services, etc. And regular and deep participation shows higher engagement. It will conduct a comprehensive and multi-dimensional assessment of the learning value-added of students from multiple dimensions, such as personal development trajectory records and participation in professional-related volunteer service activities. In implementation methods, multiple strategies have been adopted: online tests, written assignments, and so on. It will conduct a comprehensive and multi-dimensional assessment of the learning value-added of students from multiple dimensions, such as personal development trajectory records and participation in professional-related volunteer service activities.

4. Conclusion

The design of the intelligent experimental teaching platform based on VR large model technology focuses on the organic combination of the intelligent experimental teaching platform, VR large model technology, and a multi-dimensional teaching evaluation system. It aims to provide students with better learning methods, tools, and feedback. The intelligent platform for experimental teaching is the operational basis and carrier of VR large model technology and multi-dimensional teaching evaluation systems. The VR large model technology has expanded and optimized the teaching model of the intelligent experimental teaching platform, thereby facilitating the construction of multi-dimensional teaching evaluation systems. In turn, the multi-dimensional teaching evaluation systems provide real-time feedback on the teaching achievements of VR large model technology and the intelligent experimental teaching platform, which ensures the innovativeness, timeliness, and effectiveness of both.

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AI Enhanced Intangible Cultural Heritage Education in Basic Education: Practices and Challenges

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Abstract. With the advancement of information technology, AI has provided new means for the inheritance and protection of intangible cultural heritage. This article aims to explore how AI can promote the inheritance and innovation of intangible cultural heritage in the basic education stage. Through literature review and case analysis, this paper discusses the role and specific implementation strategies of AI technology in the inheritance of intangible cultural heritage, such as building a professional education system, inviting intangible cultural heritage inheritors to campus, as well as the challenges faced, such as the difficulty of technology popularization and unequal distribution of educational resources, and proposes corresponding solutions. The empirical results indicate that the rational use of AI technology can not only strengthen the protection and inheritance of intangible cultural heritage, but also enhance young people's interest and understanding of traditional culture.

Keywords. AI technology, Intangible cultural heritage, Elementary education, Cultural inheritance

1. Introduction

In the context of globalization, the protection and inheritance of intangible cultural heritage, as a common spiritual wealth of humanity, are particularly important [1]. However, traditional methods are unable to meet the rapidly changing needs of modern society, especially among young people. How to effectively spread and inherit these valuable cultural heritages has become an urgent problem to be solved.

In recent years, with the rapid development of artificial intelligence technology, new ideas and methods have been provided for the inheritance of intangible cultural heritage. By applying AI technology, not only can teaching content and forms be enriched, but

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students' interest and participation in learning can also be increased, thereby promoting the protection and development of intangible cultural heritage [2]. In addition, the use of AI technology can create personalized learning experiences, providing customized educational programs tailored to the interests and needs of different students, further enhancing learning effectiveness [3]. Therefore, exploring the practical path of AI empowering intangible cultural heritage in basic education and the challenges it faces has important theoretical significance and practical value. This method not only contributes to the preservation of cultural heritage, but also provides a new way for the younger generation to come into contact with and understand traditional culture.

2. AI empowers the inheritance and innovation of intangible cultural heritage

2.1. Theoretical framework of AI empowering intangible cultural heritage education

This study constructs a theoretical framework on how artificial intelligence (AI) can promote the inheritance and development of intangible cultural heritage in basic education based on personalized learning theory, immersive experience theory, and mobile learning theory. Firstly, personalized learning utilizes AI technology to analyze students' learning preferences, knowledge levels, and interests, tailoring learning paths for each student to improve learning outcomes. Secondly, immersive experiences utilize virtual reality (VR) and augmented reality (AR) technologies to create an immersive learning environment, allowing students to personally experience the unique charm of intangible cultural heritage and deepen their understanding and identification with traditional culture. Finally, the application of mobile technology makes it possible to access intangible cultural heritage educational resources anytime and anywhere, which not only broadens learning channels but also enhances the flexibility and convenience of learning. This theoretical framework lays the foundation for further exploration of the specific applications of AI in the recording, preservation, education popularization, and innovation of intangible cultural heritage.

2.2. The application of AI in recording and preserving intangible cultural heritage

AI technology can achieve digital preservation of cultural heritage by learning from large amounts of data to record, organize and analyze intangible cultural heritage materials. For example, image recognition technology can accurately capture and record the entire production process of handicrafts such as embroidery and ceramics, from raw material preparation to finished product completion [4]. This technology not only helps to record every step of traditional skills in detail, but also continuously provides students with visual teaching materials. Meanwhile, natural language processing technology can assist in interpreting ancient texts, folklore, and other forms of written records, transforming difficult to understand language into modern language, and extracting valuable cultural information from it [5]. In addition, voice recognition technology and motion capture technology can be used for the inheritance of music and dance, accurately recording the rhythm and melody of traditional music as well as the steps and postures of dance, ensuring that these unique art forms are fully preserved [6]. These application scenarios are shown in Table 1:

Table 1. Application examples of AI technology in the recording and preservation of intangible cultural heritage

Tool Name	Technical Overview/Function Introduction	Teaching Application Example
Image recognition system	Automatically analyze and understand image content through computer vision technology	Through comparative analysis of painting classes, student participation has increased by 40%
Text analysis platform	NLP for Semantic & Keyword Analysis	Through comparative analysis of Chinese language classes, students' comprehension speed has increased by 50%
Sound and motion capture system	Audio-Motion Capture for Performing Arts	Through comparative analysis of music classes, students' music rhythm scores have increased by 25%

2.3. Utilizing AI technology to enhance the popularization of intangible cultural heritage education

AI technology is not limited to recording and preserving intangible cultural heritage, it can also greatly improve the popularization of intangible cultural education. Firstly, a stratified sampling method is adopted to conduct a questionnaire survey among 450 students aged 7-18, analyzing the differential characteristics of different age groups across three dimensions: cognitive level (exposure to AI technology), attitude tendency (acceptance of the technology), and participation behavior (willingness to use tools). Secondly, 10 urban and rural schools are selected for a quasi-experimental study, randomly divided into an experimental group (with AI tools introduced) and a control group (using traditional teaching methods). Through comparison, students' mastery of intangible cultural heritage knowledge (assessed via a 20-question objective test) and changes in interest (measured by a 15-item scale) are evaluated. Independent sample tests using SPSS are conducted to strengthen the scientific basis of the research conclusions. Shown in Table 2.

Table 2. Application Examples of AI Technology in the Popularization of Intangible Cultural Education

Application scenarios	Technical means	Example Description
Interactive learning	AI Ed Software	Provide personalized learning paths to enhance learning interest
Virtual experience	VR/AR technology	Immersive experience of intangible cultural heritage
Online platform	Social Media AI	Support work sharing and feedback, promote cultural exchange

2.4. The role of AI in promoting innovation in intangible cultural heritage

In addition to recording and education, AI also plays an important role in promoting the innovative development of intangible cultural heritage. Leveraging AI technology, artists can produce innovative works that integrate traditional and modern elements. For example, machine learning algorithms can be employed to design culturally distinctive patterns, while neural audio synthesis techniques can transform historical audio data into contemporary musical compositions, thereby reinterpreting ancient melodies through a modern lens. In addition, AI can also help designers achieve real-time verification of creativity through rapid prototyping tools, greatly accelerating the product development process [7]. It not only enriches the connotation of intangible cultural heritage, but also injects new vitality into traditional culture, promoting the prosperity and development of cultural diversity. This enables intangible cultural heritage not only to be passed down, but also to shine with new brilliance in today's globalized world, attracting more attention and participation from young people.

Table 3. Application Examples of AI Technology in Intangible Cultural Heritage Innovation

Application area	Technical means	Example Description
Design innovation	Machine learning algorithms	Automatically generate new pattern designs
Musical composition	Data synthesis technology	Synthesize new music works based on historical audio data
Rapid prototyping	CAD/CAM Systems and AI	Accelerate the design and manufacturing of intangible cultural heritage products

3. Inheritance and Innovation Strategies of Intangible Cultural Heritage in Basic Education

3.1. Building a professional intangible cultural heritage education system

In order to better integrate intangible cultural heritage into basic education, it is necessary to establish a systematic education system. This system not only covers various stages from kindergarten to high school, but also designs corresponding curriculum content for students of different age groups. For example, in primary school, students can learn about local intangible cultural heritage projects through storytelling; In middle school, field trips or hands-on practical activities can be organized to deepen students' understanding and experience [8]. By selecting folk literature as the main content in intangible cultural heritage, we explore an interdisciplinary project-based teaching model based on AI, as shown in Figure 1.

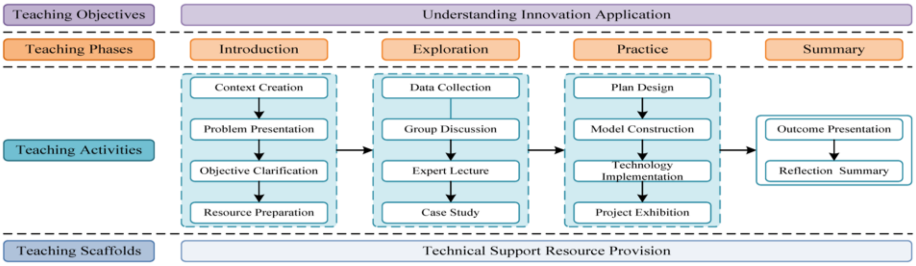

Figure 1. Interdisciplinary project-based teaching model based on AI

3.2. Inviting inheritors of intangible cultural heritage to campus

Direct contact is widely recognized as one of the most direct and effective ways to understand intangible cultural heritage. Therefore, schools should regularly invite inheritors of representative intangible cultural heritage projects to enter the classroom and share their skills and experiences. This type of interaction not only enhances students' intuitive understanding of intangible cultural heritage, but also helps to stimulate their interest and love for traditional culture. For example, in an educational practice, primary school students show strong interest and high enthusiasm in participating in Paper Cuttings art activities, as shown in Figure 2. This teaching method reflects an effective way to integrate intangible cultural heritage into basic education, while also providing an opportunity for the younger generation to experience traditional art up close.

Figure 2. Intangible Cultural Heritage Enters Campus activity

3.3. Innovation of AI based intangible cultural heritage inheritance methods

In addition to traditional teaching methods, AI technology can also be used to explore new ways of inheriting intangible cultural heritage. For example, developing interactive learning software based on VR/AR technology, allowing students to feel as if they are in the birthplace of intangible cultural heritage [9]; Or create an online platform for teachers and students to exchange experiences and showcase works, in order to create a good learning atmosphere, as shown in Figures 3.

Figure 3. AI based online classroom management platform

4. The challenge of inheriting and innovating intangible cultural heritage

4.1. Difficulty in popularizing technology

Despite significant achievements in various fields, the application of AI technology in the protection of intangible cultural heritage is still in its early stages. The difficulties faced by technology promotion are mainly reflected in the fact that remote areas lack sufficient funding, resulting in outdated hardware facilities and inability to provide necessary technical support, which limits the application scope of AI; Meanwhile, the low level of local economic development and lack of private investment interest further exacerbate the problem of resource scarcity. Therefore, in order to lower the technological threshold and improve the popularization rate, it is necessary to increase funding for cultural projects in remote areas and encourage diversified financing channels; At the same time, policy implementation and targeting should be strengthened to ensure the effective implementation of various measures. By improving infrastructure conditions and optimizing policy environment, promote the widespread application and development of AI technology in the field of intangible cultural heritage.

4.2. Unequal distribution of educational resources

The uneven distribution of educational resources is also one of the important factors restricting the inheritance and innovation of intangible cultural heritage. On the one hand, high-quality educational resources are often concentrated in big cities or developed areas, while students in some underdeveloped areas find it difficult to access educational resources of equal quality. On the other hand, even within the same region, differences in economic and technological conditions between schools can lead to uneven levels of education. This imbalance not only affects students' learning experience, but also hinders the widespread dissemination and in-depth understanding of intangible cultural heritage.

4.3. The difficult problem of integrating tradition and modernity

Balancing the relationship between tradition and modernity is a highly challenging task in the process of inheriting and innovating intangible cultural heritage. On the one hand, intangible cultural heritage carries profound historical heritage and unique national spirit, emphasizing faithful inheritance of tradition. For example, traditional wood carving techniques have been passed down for hundreds of years, and every carving and pattern design contains the wisdom and emotions of our predecessors. Once changed arbitrarily, it may lose its original cultural value. On the other hand, the rapid development of modern society requires intangible cultural heritage to keep pace with the times and incorporate new elements to maintain vitality [10]. If intangible cultural heritage remains stagnant and does not integrate with modern technology and aesthetics, it will be difficult to attract the attention of the younger generation and may ultimately be eliminated by the times.

5. Conclusion

This article explores the application and challenges of AI technology in basic education of intangible cultural heritage. Research has shown that AI efficiently records and preserves intangible cultural heritage through digital means, and enhances cultural identity and participation among adolescents through interactive learning and VR/AR experiences. However, the difficulty of popularizing technology, the imbalance of educational resources, and the integration of tradition and modernity remain the main challenges. Future research will continue to explore more effective strategies and technological solutions, and make reasonable use of AI technology to continuously enhance the attractiveness and vitality of intangible cultural heritage, in order to strengthen the effectiveness of intangible cultural heritage in basic education.

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Integrating Intangible Cultural Heritage into Basic Chinese Language Education via Big Data

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Abstract. With the increasing emphasis on the protection and inheritance of intangible cultural heritage, how to effectively integrate these precious cultural resources into basic Chinese language education has become an important issue. However, traditional teaching methods are difficult to meet the personalized learning needs and the requirements for efficient dissemination of intangible cultural heritage. This study utilizes big data technology to explore its role in information preservation, cultural dissemination innovation, and educational resource development, and analyzes the contribution of big data to the optimization of Chinese language teaching evaluation and curriculum integration. Research has shown that big data technology not only significantly improves the preservation and dissemination of cultural heritage, but also promotes personalized learning in Chinese language teaching, enhancing students' cultural identity and social responsibility. This study provides a new perspective for the integration of cultural heritage protection and basic Chinese language education, demonstrating the important practical significance and promotional value of big data technology in this field.

Keywords. Big data technology, Intangible cultural heritage, Innovation in Chinese Language Teaching

1. Introduction

In the context of globalization and informatization, intangible cultural heritage, as a living carrier of national memory and cultural genes, is facing unprecedented challenges in its inheritance and development [1]. At the same time, as a key area for cultural inheritance and value shaping, basic Chinese language teaching urgently needs to innovate its teaching mode and resource system through technological innovation [2].

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The research is funded by the 2024 Hunan Provincial Social Science Achievement Evaluation Committee's general project "Research on the Pathways of Promoting Spiritual Life Prosperity through Hu-Xiang Intangible Cultural Heritage" (Project No. XSP24YBC458), the 2024 Hunan Provincial Education Science "14th Five-Year Plan" provincial youth funding project "Integration of Hu-Xiang Intangible Cultural Heritage into Traditional Virtue Education for Contemporary College Students" (Project No. ND249554), and the 2023 Hunan Province University Ideological and Political Work Research Project "Integration of Hu-Xiang Intangible Cultural Heritage into Ideological and Political Education for Contemporary College Students" (Project No. 23A47).

Big data technology, with its powerful data collection, intelligent analysis, and precise dissemination capabilities, provides unprecedented opportunities for the protection of intangible cultural heritage and innovation in Chinese language teaching. In recent years, significant progress has been made in the digital protection of intangible cultural heritage based on big data, such as achieving permanent preservation and global sharing of cultural resources through technologies such as stereoscopic scanning and cloud storage; Research in the field of education has revealed the enormous potential of big data in personalized teaching, learning behavior analysis, and interdisciplinary resource integration [3].

This article is based on cutting-edge research results, systematically analyzing the application path of big data technology in intangible cultural heritage information management, precise dissemination, and educational scene innovation, providing theoretical support and practical paradigms for the modernization of traditional cultural education.

2. The Application of Big Data Technology in the Inheritance of Intangible Cultural Heritage

2.1. Big data technology optimizes the preservation of intangible cultural heritage information

Big data technology plays a crucial role in the digital preservation of intangible cultural heritage. For instance, in the case of Beijing Opera, big data technologies such as stereoscopic scanning and cloud storage have been employed to create high-definition digital archives of performances and costumes. These archives not only preserve the intricate details of traditional opera but also ensure that these resources can be accessed globally. This process involves using specialized software like Autodesk ReCap Photo for image stitching and cloud services like AWS S3 for secure storage, thereby enhancing both the security and accessibility of these invaluable cultural assets.

In the process of information collection, big data technology can process massive amounts of data and comprehensively understand various aspects of intangible cultural heritage, such as historical background, technical characteristics, and inheritance lineage, through data mining and pattern recognition, providing important references for subsequent research and inheritance work. Take Beijing Opera, Kunqu Opera, Paper Cuttings, calligraphy and other intangible cultural heritage projects as examples [4]. These cultural heritage carries rich historical and cultural information, but faces the risk of loss. Big data technology uses digital methods such as stereoscopic scanning, image and text scanning, and digital photography to preserve intangible cultural heritage materials in an authentic, comprehensive, and convenient manner. The application of technologies such as magnetic media storage and optical media storage has improved the security and stability of intangible cultural heritage data.

Using big data technology to establish an intangible cultural heritage database and online display platform not only enriches the public's cultural resource experience, but also provides convenient tools for professionals, as shown in Table 1:

Table 1. Comparison of Intangible Cultural Heritage before and after Digital Preservation

Attributes of Preservation Method	Before Digital Preservation	After Digital Preservation
Storage Format	Paper, Physical Objects	Digital Files
Security	Prone to Damage	High Security
Accessibility	Limited	Global Access
Storage Cost	High	Low

2.2. Innovation in the dissemination of intangible cultural heritage based on big data technology

Big data technology provides strong support for the dissemination of intangible cultural heritage by analyzing users' browsing behavior and interest preferences. Using data such as users' browsing records, search history, and social media interactions on the Internet, big data technology can accurately grasp users' interests and needs for intangible cultural heritage. For example, an analysis conducted by our team on the online behavior of Kunqu Opera enthusiasts revealed that over 70% of users aged between 18-35 prefer short video formats for learning about traditional operas. Based on this insight, we developed a series of engaging short videos featuring young actors performing classic scenes from Kunqu Opera. These videos were distributed via popular platforms like Douyin and Kuaishou, resulting in a significant increase in engagement rates, with likes and shares increasing by 45% within the first month of release.

Compared to dissemination methods based on big data technology, traditional offline activities have limited audience reach and higher costs [5]. Big data technology can efficiently expand the audience by analyzing users' network usage habits and selecting suitable online platforms for efficient dissemination, such as social media, short video platforms, etc. For example, targeting young people who love Peking Opera, big data technology analysis can accurately locate the target audience, select the most suitable communication channels and methods, such as social media platforms, online live streaming, etc., effectively improving the dissemination efficiency and acceptance of intangible cultural heritage [6].

According to market research data, the contribution of different communication channels to the dissemination of intangible cultural heritage is shown in Figure 1.

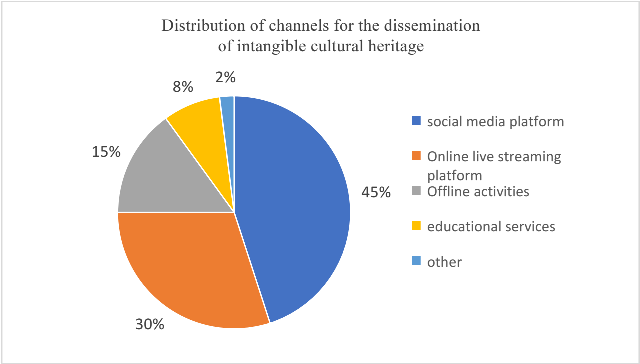

Figure 1. Distribution of channels for the dissemination of intangible cultural heritage

2.3. Big data technology promotes the development and utilization of intangible cultural heritage education resources

Big data technology can not only effectively collect, organize, and analyze intangible cultural heritage educational resources from various sources, including written records, images, and videos, but also form a structured database through classification and tagging processes [7]. For example, in developing educational materials for Paper Cutting Art, we utilized machine learning algorithms to automatically categorize and tag thousands of historical documents and skill demonstration videos. This automated system significantly reduced manual labor and improved accuracy, allowing teachers and students to easily access comprehensive learning materials tailored to their specific needs. As a result, student engagement increased by 30%, and feedback indicated a deeper understanding and appreciation of paper cutting traditions.

Big data technology has promoted the innovation of intangible cultural heritage education models, supported the development of personalized teaching plans, and made the presentation of intangible cultural heritage education resources more vivid and interesting through modern technological means. With the help of big data technology, learners' interest preferences and specific needs can be deeply explored, and the content and activities of intangible cultural heritage education that are more suitable for students' needs can be designed. For example, Paper Cuttings, Kunqu Opera and shadow play can be integrated into modern multimedia teaching, and learning modules with strong interaction can be produced, as shown in Table 2.

Table 2. Application Examples of Big Data Technology in Intangible Cultural Heritage Education

Intangible Cultural Heritage Project	Big Data Technology Application	Educational Development Outcome
Paper Cutting Art	Data-driven demand analysis, VR interactive courses	Increase students' interest and hands-on ability
Kunqu Opera	Social media data analysis, customized course design	Attract more students to participate in Kunqu learning
Shadow Play	Student feedback data collection and analysis, interactive teaching software	Optimize teaching resources, improve teaching quality

3. The Application of Big Data Technology in Innovative Chinese Language Teaching in Primary and Secondary Schools

3.1. Big data technology optimizes the evaluation method of primary school Chinese language teaching

Traditional evaluation of primary school Chinese language teaching often focuses on outcome indicators such as exam scores, neglecting attention to the entire learning process of students [8]. After introducing big data technology, it is possible to obtain more comprehensive data support and achieve accurate evaluation by tracking students' learning trajectories throughout the process. This kind of teaching evaluation based on big data technology can not only reflect students' knowledge mastery, but also reveal their thinking habits, interests and hobbies, and help teachers develop more targeted teaching plans, improve teaching quality and learning effectiveness.

3.2. Inviting inheritors of intangible cultural heritage to campus

The application of big data technology has enriched Chinese language teaching resources in primary and secondary schools and improved teaching efficiency. For example, when explaining calligraphy art, teachers can use big data technology platforms to integrate high-quality educational resources and design teaching plans that meet students' personalized needs [9]; The online evaluation system can provide real-time feedback on students' learning status, making it easier for teachers to adjust teaching strategies in a timely manner; Using multimedia teaching methods makes the classroom more lively and interesting, stimulating students' interest in learning [10].

3.3. Big data technology supports innovative practices in Chinese language teaching in primary and secondary schools

Big data technology has not only changed the traditional teaching mode, but also brought more possibilities for Chinese language teaching. Through big data technology, teachers can gain a deep understanding of students' learning preferences and needs, and design teaching activities that are more tailored to students' characteristics based on this. For example, when teaching articles about shadow puppetry, combining multimedia to showcase actual performances of shadow puppetry allows students to appreciate literary works while experiencing the charm of traditional culture [11].

4. Big Data Technology Facilitates the Integration of Intangible Cultural Heritage with Primary and Secondary School Chinese Language Teaching

4.1. Integrating Intangible Cultural Heritage into Chinese Language Teaching Content in Primary and Secondary Schools

Incorporating intangible cultural heritage into the Chinese language teaching system for primary and secondary schools is one of the effective ways to inherit and promote excellent traditional Chinese culture. For example, by using big data technology to analyze and understand students' interests in Peking Opera, a series of colorful teaching activities can be carried out around these themes, such as holding special lectures on Peking Opera culture, organizing experience classes on handmade facial makeup, etc., in order to stimulate students' love for local culture [12], as shown in Figure 2.

Figure 2. Holding a Special Lecture on Beijing Opera Culture

4.2. Utilizing big data technology to enhance the teaching effectiveness of intangible cultural heritage

In order to better evaluate the actual effectiveness of teaching intangible cultural heritage, it is necessary to use big data technology to track and analyze students' learning behavior. By comparing the changes in students' performance before and after participating in the course, teachers can identify existing problems and take corresponding measures to improve them. At the same time, big data technology can also recommend intangible cultural heritage learning resources suitable for each student's personal development based on their characteristics, provide multi-dimensional diagnostic evaluation, and truly achieve personalized teaching, as shown in Figure 3.

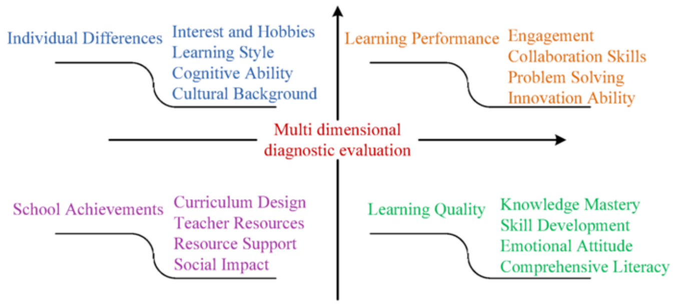

Figure 3. Multi dimensional Diagnostic Evaluation System for Students

4.3. Innovative Model for Integrating Intangible Cultural Heritage with Chinese Language Teaching in Primary and Secondary Schools

With the support of big data technology, explore the establishment of a new teaching model that combines intangible cultural heritage with Chinese language teaching in primary and secondary schools. This model emphasizes student-centered approach, focusing on cultivating their comprehensive literacy and sense of social responsibility. By integrating various teaching resources, adopting diverse teaching methods and technological means, students can learn knowledge in a relaxed and enjoyable atmosphere, while deeply experiencing the unique charm of excellent traditional culture, as shown in Figure 4.

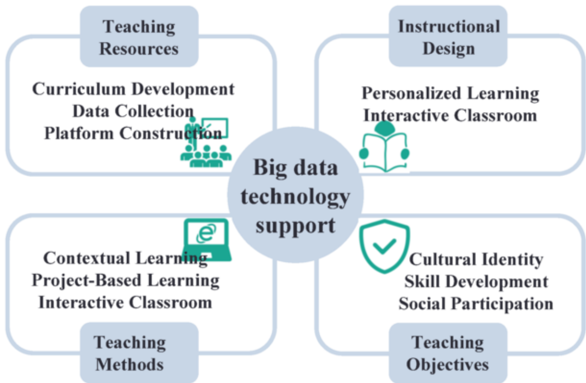

Figure 4. Integration Model of Intangible Cultural Heritage and Chinese Language Teaching in Primary and Secondary Schools

5. Conclusion

This article explores the innovative integration model of intangible cultural heritage and Chinese language teaching in primary and secondary schools based on big data technology. Analysis shows that in Chinese language teaching, big data technology can accurately evaluate students' learning trajectories and interest preferences, provide personalized teaching guidance, and improve teaching quality; By integrating intangible cultural heritage into Chinese language teaching content and adopting forms such as multimedia interactive classrooms, students' cultural identity and social responsibility have been significantly improved. This not only enriches teaching resources and methods, but also provides new paths and perspectives for traditional cultural education, which has important practical significance and promotion value.

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The Inheritance Strategy of Intangible Cultural Heritage in Rural Revitalization from the Perspective of Lifelong Education

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Abstract. This paper aims to explore the pathways for protecting and inheriting intangible cultural heritage (ICH) within the context of China's rural revitalization strategy. By examining its significance, existing challenges, and successful practices in the process of rural cultural revitalization, the study proposes a three-dimensional inheritance framework centered on community participation, digital innovation, and educational promotion. Specifically, it investigates the roles of policy guidance and grassroots engagement, the application of digital technologies in ICH preservation, as well as the popularization of ICH-related education and the development of a lifelong learning system. The research seeks to offer both theoretical insights and practical references for achieving sustainable protection and intergenerational transmission of ICH throughout the rural revitalization process.

Keywords. The rural revitalization strategy, ICH, Digital technology, Lifelong education

1. Introduction

Against the backdrop of national and international policies jointly committed to revitalizing rural communities, the rural revitalization strategy has emerged as a key measure to promote rural modernization in the new era. ICH encompasses folk customs, handicrafts, festivals, traditional music, and oral traditions, forming the core of rural culture. It not only carries rich historical memory and national spirit, but also plays a crucial role in enhancing cultural identity in rural areas and promoting economic sustainability [1].

However, in the current process of rapid modernization, the protection and inheritance of ICH face multiple challenges, including population aging, weakened cultural interest caused by the migration of the younger generation to cities, lack of

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formal and informal systematic learning pathways, and threats to the authenticity and integrity of ICH from market and commercialization pressures. Such challenges underscore the urgency of establishing effective mechanisms for the preservation and intergenerational transmission of ICH under the framework of rural revitalization.

In view of this, this article aims to explore the protection and inheritance path of ICH that meets the needs of the new era, and particularly emphasizes lifelong education as a key tool in this process. By delving into the concept of ICH and its importance in promoting sustainable social, cultural, and economic development, this article will conduct a detailed analysis from three dimensions: policy support, digital technology innovation, and education popularization based on a lifelong learning system. Particular attention is paid to how to strengthen the safeguarding and transmission of ICH through educational means in order to build a sustainable ecosystem of ICH. In addition, this article will also discuss strategies for integrating government, community, school, and family forces, providing practical guidance and theoretical basis for the protection and inheritance of ICH in rural revitalization.

2. The role of policy guidance and community participation in safeguarding ICH

2.1. Construction of Government Role and Policy Support System

Governments play a crucial role in safeguarding ICH. Firstly, the formulation and improvement of relevant laws and regulations, such as the Law of the People's Republic of China on ICH, provide legal protection for the protection of ICH. Secondly, provide financial support and establish special funds to support activities such as recording, preserving, and inheriting ICH projects. In order to support the protection of ICH, the central government has allocated approximately 826 million yuan for the protection of ICH in 2024. In addition, establish a system of ICH list to recognize and protect ICH projects with significant value. These measures together form a solid foundation for the protection of ICH, as shown in Table 1.

Table 1. 2024 National Non-material Cultural Heritage Protection Fund Budget (Unit: Ten Thousand Yuan)

Serial Number	Province	Key Projects	General Projects
1	Fujian	3081	1988
2	Henan	2910	1836
3	Shandong	1297	2547
4	Sichuan	1467	2355
5	Yunnan	1467	2258

2.2. Innovation and Practice of Community Participation Mechanism

As the core subject of ICH inheritance, the role of the community cannot be ignored. For example, the Old Town of Lijiang in Yunnan Province has attracted a large number of domestic and foreign tourists by organizing traditional Dongba culture exhibitions, handicraft exhibitions and various folk activities [2]. Xijiang Qianhu Miao Village in Leishan County, Guizhou Province is one of the largest Miao ethnic settlements in China. It focuses on ICH such as Miao silver jewelry making skills and Miao embroidery, and has launched a series of cultural tourism experience projects. Active participation of community members in the organization and promotion of ICH activities to enhance the vitality and impact of ICH [3]. Many rural areas in China have begun to promote and apply these models, with typical cases shown in Table 2.

Table 2. Typical Practices and Effectiveness Evaluation Results of Protecting ICH in Villages and Communities

Village/Community	ICH Projects	Unique Practices	Achievements
Lijiang Ancient Town, Yunnan	Dongba Culture, Handicraft Exhibitions, Folk Activities	Regular cultural festivals, encouraging local participation	Attracts tourists, enhances local identity, boosts tourism
Xijiang Qianhu Miao Village, Guizhou	Miao Silver Ornaments Craft, Miao Embroidery	Workshops on craft making, traditional festival celebrations, cultural museums	Increases young generation's interest, promotes living heritage, raises regional profile
Anchang Ancient Town, Zhejiang	Traditional Rice Cake Making, Preserved Duck Display	AnnualPreserved Duck Festival, hands-on experience for visitors	Boosts sales of local specialties, strengthens community bonds, promotes cultural tourism
Jinli Street, Chengdu, Sichuan	Sichuan Opera Face-Changing, Paper-Cutting, Sugar Painting	Multiple ICH demonstration spots with interactive experiences	Enhances public knowledge of Sichuan culture, attracts numerous visitors, stimulates local commerce

2.3. Exploration of Cross Regional Cooperation and Resource Sharing Models

Cross regional cooperation helps to expand the influence of ICH, promote cultural exchange and resource sharing between different regions. By establishing a nationwide platform for sharing ICH resources, not only can geographical boundaries be broken and scattered ICH resources be integrated, but also regional exchanges of ICH can be strengthened, providing new opportunities for the protection, inheritance, and development of ICH projects. Cross regional talent exchange mechanisms, such as organizing seminars and training courses, not only promote the inheritance and development of ICH skills, but also inject fresh blood into rural revitalization.

Table 3. Forms and Main Achievements of Cross regional Cooperation

Non-Heritage Project	Collaboration Form	Participating Parties
Traditional Crafts	Seminars	Culture Dept., Ed. Inst., Local Gov.
Folk Music & Dance	Workshops	Arts Groups, Unis., Community Orgs.
Traditional Festivals	Heritage Exhibitions	Museums, Tourism Bureaus, Media
Local Cuisine	Cultural Products	Ag. Cooperatives, Food Assocs., Designers
Ancient Building Restoration	Research Projects	Architecture Schools, Historic Preservation Orgs., Local Gov.
Craft Skills Exchange	Visit Programs	Craftsmen, Industry Assocs., Local Gov.

3. The Application of Digital Technology in the Inheritance of ICH

3.1. Digital recording and preservation technology

By utilizing technologies such as 3D modeling and image recognition, digital collection of ICH techniques such as embroidery, wood carving, and ceramics is carried out, and a dynamic database is established. For example, developing an "AI embroidery pattern generator" to generate innovative designs by analyzing traditional pattern patterns through algorithms [4]. Develop AI based virtual interactive experiences, utilizing augmented reality (AR) and virtual reality (VR) technologies to create immersive cultural experience environments, allowing visitors to experience the unique charm of ICH through smart devices or virtual platforms. For example, embedding an AR navigation system in the protection and restoration of ancient cities allows tourists to scan building components and trigger virtual scenes, restoring the teaching scene of the Confucian Palace in Haiyang County during the Song and Yuan dynasties. Through digital preservation, even if the original items are damaged or lost over time, their data form can still be preserved for a long time, ensuring the continuity and accessibility of cultural heritage. An example of AI empowering the inheritance of ICH [5], as shown in Figure 1.

Figure 1. Artificial Intelligence Creating Digital Shadow Puppetry Collectibles

3.2. Leveraging Big Data for Enhanced Cultural Heritage Management and Personalized User Engagement

The application of big data analytics offers transformative potential in the management and promotion of ICH, enabling more effective audience engagement and personalized user experiences. By collecting and analyzing vast amounts of data from social media interactions, online museum visits, and educational programs, we can gain valuable insights into audience preferences and engagement levels. This information is crucial for tailoring personalized learning experiences and optimizing cultural heritage projects. For example, big data analytics can be used to monitor visitor interactions with digital shadow puppetry collectibles across different demographics and regions. Insights gained from this analysis help cultural institutions design more engaging exhibitions and interactive experiences that resonate better with diverse audiences. Furthermore, predictive analytics enabled by big data can forecast trends in visitor behavior, helping heritage managers allocate resources efficiently and plan future events strategically.

Moreover, integrating big data with machine learning models allows for the creation of recommendation systems tailored to individual users' interests. These systems suggest specific ICH projects or events based on past behaviors and preferences, thereby increasing participation rates and fostering a stronger sense of cultural identity among community members. Such targeted approaches not only enhance the visibility and accessibility of ICH but also contribute to its sustainable development within the framework of rural revitalization.

3.3. Digital Dissemination and Education Platform Construction

The Internet opens new avenues for the dissemination of ICH. Online museums, online courses, and other forms have significantly enhanced the public's awareness and enthusiasm for participating in ICH. Social media and short video platforms have widely spread the production process and stories of ICH, such as Tencent's "Digital Scripture Cave" which uses VR technology to immerse users in the restoration of Dunhuang murals [6]; Luoyang Tang Sancai uses 3D scanning to generate NFTs and sells them in limited quantities to attract young audiences [7]; Tiktok initiated the "Partnership Program for ICH", which supported more than 2000 inheritors of ICH to create short videos [8]. Among them, face changing of Sichuan Opera, guqin performance and other contents were broadcast more than 10 billion times, which not only improved the influence of ICH, but also promoted cross-cultural communication and understanding. CCTV's "China in ICH" showcases the cultural stories behind the skills in the form of "ICH+plot interpretation", combining education and entertainment to make it easier for audiences to accept ICH. Through these innovative methods, ICH has regained new vitality in the digital age and rapidly spread with the widespread coverage and interactivity of online platforms. The digital dissemination of ICH is highly popular among young people, as shown in Figure 2.

Figure 2. Tourist Experience in the "Search for Dunhuang" Project

3.4. Digital Innovation and Marketization of ICH Products

E-commerce platforms and digital games provide new opportunities for the marketing of ICH products. For example, the successful experience of online experiential sales of Miao silver jewelry through virtual reality technology demonstrates the potential of digital technology in the marketization of ICH products. In addition, the development of innovative forms such as ICH themed games has not only attracted the attention of young consumers, but also injected new vitality into the inheritance of ICH. According to Taobao data, in 2022, the number of inheritors of ICH on the platform increased by 34% annually, and the sales of good ICH products increased by 668% year-on-year. The annual transaction volume of ICH related products has exceeded 100 billion yuan for the first time, reaching 107.32 billion yuan, a year-on-year increase of 37.7%, which is more than five times the growth rate of total retail sales of consumer goods during the same period [9].

The consumption of ICH is showing an overall growth trend, and the consumption of ICH is increasingly closely linked to people's better lives. The consumption circle of ICH is forming, and the brands and industrial belts of ICH are continuously developing. The annual overview of e-commerce consumption for ICH is shown in Figure 3.

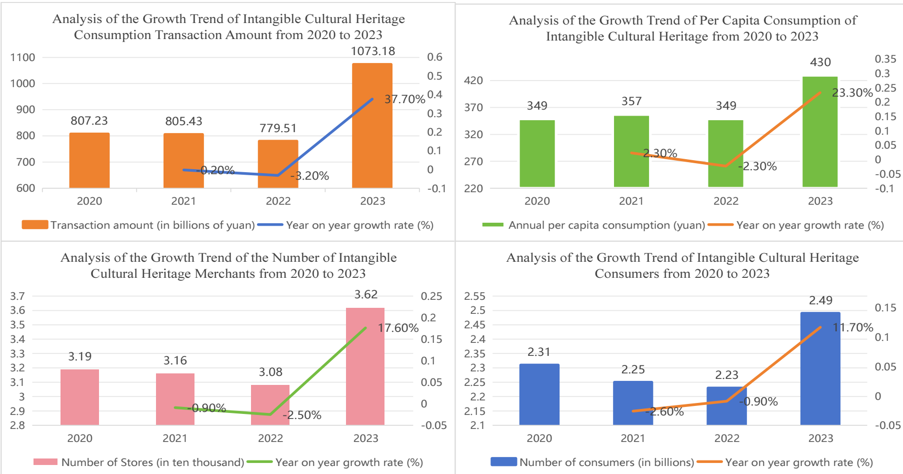

Figure 3. Overall Growth Trend of ICH Consumption

4. Popularization of ICH Education and Construction of Lifelong Learning System

4.1. Integration of School Education and ICH Curriculum

Incorporating ICH education into the school curriculum system is crucial for cultivating students' sense of cultural identity and inheritance consciousness. Some regions have already started experimenting, such as developing school-based textbooks and inviting inheritors into classrooms. These practices not only allow students to understand the local traditional culture, but also stimulate their interest and love for ICH. In addition, schools can organize on-site inspection activities to lead students into ICH workshops or museums, and personally experience the charm of traditional skills. At the same time, combining modern technological means to make the teaching of ICH more vivid and interesting. This not only deepens students' understanding of ICH, but also enhances their practical abilities, laying the foundation for future inheritance work.

4.2. Community Education and Lifelong Learning Platform Construction

Building a lifelong learning platform within the community, encouraging the elderly to impart skills to young people while also learning new skills, is one of the effective ways to inherit ICH. By organizing various forms of training courses to meet the learning needs of different age groups, cultural exchange and inheritance within the community have been promoted. The community can regularly hold exhibitions of ICH skills, inviting experts and inheritors to give on-site demonstrations and explanations, attracting residents to participate and experience. In addition, establish an online learning resource library to provide rich learning materials on ICH, making it convenient for everyone to access and learn at any time. This combination of online and offline not only enriches the cultural life of community residents, but also provides new ideas and methods for the inheritance and development of ICH.

4.3. Cultivation and incentive mechanism for inheritors of ICH

In order to attract more young people to participate in the inheritance of ICH, it is necessary to establish an effective mechanism for cultivating and motivating inheritors. Establish various incentive measures such as scholarships and entrepreneurship support to provide necessary support for inheritors. In addition, the power of the media can be utilized to publicize the deeds of the inheritors of the ICH, raise the awareness of society as a whole of the value of the ICH, and create a favourable atmosphere in which society as a whole pays attention to and supports the protection of the ICH. Through these comprehensive measures, we aim to ensure the sustainable inheritance and development of ICH in the context of the new era.

5. Conclusion

Under the strategy of rural revitalization, the protection and inheritance of ICH is a systematic project that requires joint efforts from the government, communities, inheritors, and all sectors of society. A comprehensive approach integrating policy support, digital innovation, and educational outreach contributes significantly to the preservation and transmission of ICH, while also providing cultural impetus for the revitalization of rural areas. To meet the demands of the new era, continued emphasis should be placed on enriching theoretical research and expanding practical applications in the field of ICH protection. Establishing a more systematic and sustainable protection mechanism will ensure that ICH remains vibrant and relevant in modern times.

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Exploration and Practice of Educational Mode That Integrates "Post-Course-Competition-Certificate" in Mechatronics Technology Profession of Higher Vocational College

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Abstract: The integration of "posts-courses-competitions-certificates" is an important way to achieve in-depth integration of industry and education which is highly conducive to cultivating high-quality technical and skilled talents. Taking the Mechatronics Technology Major of Qingyuan Polytechnic as an example, the practice process of "Post-Course-Competition -Certificate" integration is elaborated based on an in - depth analysis of the ideas of such integration. The content includes the construction of an integrated curriculum system for "post-class-competition-certification", the educational model of "three stages-multiple venues- three cycles", and the establishment of a four-in-one evaluation system encompassing "course teaching-skill competitions-industry certification-corporate assessment". Meanwhile, an analysis and discussion were conducted on how to deepen the integration of industry and education, strengthen the construction of teacher teams, and improve institutional guarantees in the practical process, as well as the corresponding solutions.

Keywords: higher vocational college; "post-course-competition-certificate"; mechatronics technology; personnel training mode; teaching reform

1 Introduction

The core mission of vocational education is to nurture highly skilled technical professionals in accordance with industrial advancements. The launch of pilot initiatives for the 1+X certificate system was formally initiated in 2019, as outlined in the *National Implementation Plan for Vocational Education Reform*. In October 2021, Vice-Premier Sun Chunlan emphasized the necessity to further refine the "three-teaching reform" (Teachers, Textbooks, and Teaching Methods) and "post-course-competition-certificate" comprehensive education framework to enhance the caliber of education during the National Conference on Vocational Education. In that same year, the State Council promulgated the *Opinions on the Promoting the High-Quality Development of Modern Vocational Education,* in which it emphasized

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the necessity of enhancing the integration between education and industry, fostering collaborative partnerships between educational institutions and enterprises, and refining the “post-course-competition-certificate” comprehensive education mechanism. Since then, a substantial amount of theoretical and practical exploration on the integration of the “post-course-competition-certificate” has been carried out by vocational colleges and universities across the country, yielding specific results. Nevertheless, as the research remains in its infancy, there remain a number of unresolved issues [1-6]. It is therefore imperative to undertake a comprehensive investigation into the curriculum system, educational approach, and evaluation system within the context of the “post-course-competition-certificate” integration.

2 Meaning of “Post-Course-Competition-Certificate” Integration

2.1 Improve students' technical skills

The integration of the “post-course-competition-certificate” represents the incorporation of both “competition” and “certificate” into the conventional integrated “post-course” curriculum system. The integration of skill competition standards into the curriculum system, alongside the establishment of a multi-level skill competition platform spanning “department, school, city, province”, has the potential to significantly enhance students' technical skill levels, which is achieved through a series of competition activities, including full participation in departmental competitions, with 30% participation in school-level competitions, and selective participation in city and provincial competitions. Concurrently, the integration of vocational skill level certificate standards into the curriculum system, encompassing certification training, certification selection, formal certification, and other mechanisms, serves to further enhance the cultivation of students' core competencies for post.

2.2 Deepen the integration of industry and education

The integration of the “post-course-competition-certificate” represents a significant enhancement and augmentation of the integration of the “post-course”. The assessment standards for skill competitions and the standards for vocational skill level certificates frequently derive from the core competencies required in typical job positions within industry enterprises, with an emphasis on cultivating fundamental professional abilities and significant technical skill levels. Consequently, the integration of “competition-certificates” can be regarded as a conduit for the integration of industry and education, which is of paramount importance for the cultivation of highly skilled technical professionals that are well-suited for professional posts.

2.3 Improve students' enthusiasm and sense of achievement

The organization of skills competitions and certification represents a significant element of the integration of “post-course-competition-certificate”. The organization of a series of competitions at the department, school, city, and province level will allow students to produce their works while awarded certificates and prizes in commendation meetings, thereby enhancing their enthusiasm and sense of achievement. Furthermore, it is anticipated that the award certificate of the skill competition, as well as the vocational skill level certificate, will confer an advantageous position to students when engaging in the process of securing internship and employment opportunities, thus enabling them to identify high-quality enterprises and further enhance their sense of accomplishment.

3 Concept of "Post-Course-Competition-Certificate" Integration

In order to realize the profound integration of the "post-course-competition-certificate" paradigm, it is imperative to carry out a comprehensive reform of the curriculum system, the educational mode, and the evaluation system. The concept of "post-course-competition-certificate" integration is illustrated in Figure 1.

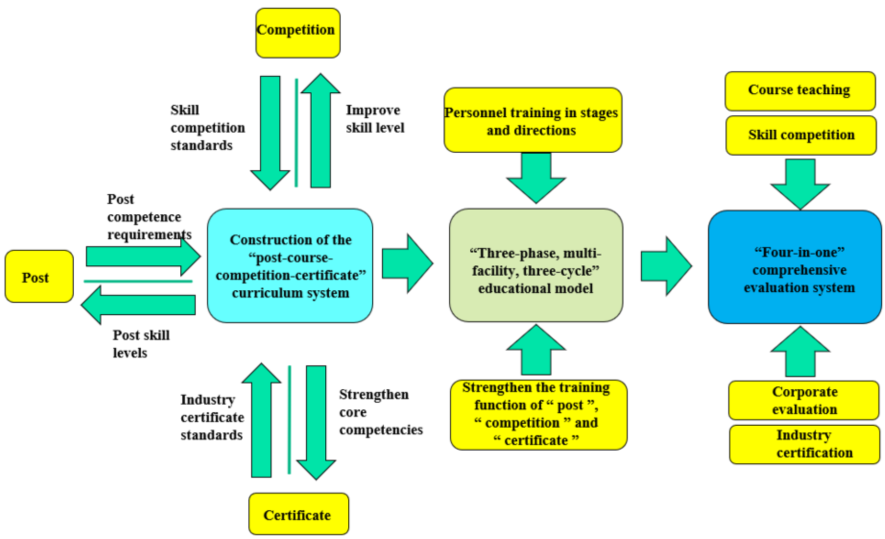

Figure 1. The concept of "post-course-competition-certificate" integration

In the first instance, it is essential to establish an integrated "post-course-competition-certificate" curriculum system. The professional curriculum system of vocational colleges and universities is customarily derived through a thorough analysis of post-specific competencies. However, this system does not always align with the criteria of skill competitions or vocational skill levels. Consequently, a crucial step that involves the standardization of evaluation criteria for professional skill competitions and the vocational skill level certificate, and the integration of relevant knowledge and skill components into the existing curriculum system should be conducted. Secondly, the integration of the "post-course-competition-certificate" must lead to a reform of the personnel training mode. The prevailing personnel training mode places considerable reliance on conventional classroom teaching for the dissemination of knowledge and the development of skills. In contrast, the integration of the "post-course-competition-certificate" is expected to fulfil a complementary and reinforcing function of "competition-certificate", augmenting the effectiveness of classroom teaching. In addition, it is imperative to refine and enhance the existing system for evaluating students' academic performance. The prevailing paradigm of academic evaluation, predicated solely on examination results, is deemed inadequate when viewed from the vantage point of this multifaceted integration of "post-course-competition-certificate". Instead, an evaluation and assessment system that is diversified and considers all aspects of student evaluation is recommended, including those aspects related to post, competition, and certification.

4 Implementation Path of "Post-Course-Competition-Certificate" Integration

4.1 Construct a course system integrating "post-course-competition-certificate"

A summary of the core knowledge and skill-related points required for mechatronics-related skill competitions, such as "CAD Mechanics Design", "Mechatronics Technology", "Digital Twin Simulation and Troubleshooting", "Digital Transformation of Manufacturing Units", "Numerical Control Maintenance and Assembly", "Modern Electrical Regulation", and so on, is presented in Table 1: Analysis Table of Knowledge and Skill-related Points in the "Skill Competition" of Mechatronics Technology Profession (taking the "CAD Mechanics Design" competition as an example).

Table 1. Analysis Table of Knowledge and Skill-related Points in the "Skill Competition"

Competition Name	Core Knowledge and Skill-related Points	References
"CAD Mechanics Design"	Competition 5-1. Master the knowledge of machinery and national standards for mechanical drawing. Competition 5-2 Familiar with ISO drawing standards and industry standards; Competition 5-3. Master the structural characteristics, working principle and specific application of typical mechanical transmission mechanism in enterprise production practice; Competition 5-4. Familiar with the working principle and characteristics of commonly used components and their connection relationship with each part; Competition 5-5. Familiar with the national standards of geometric accuracy of mechanical parts; Competition 5-6. Master the limits and fits, geometric tolerances and their labelling methods; Competition 5-7. Familiar with the materials of parts and know their common heat treatments; Competition 5-8. Familiar with the machining methods of parts and their process flow, and know the surface structure of parts and their application requirements in production; Competition5-9. Be able to draw mechanical engineering drawings on computer for typical components or parts; Competition 5-10. Be able to carry out quality inspection of parts for typical components or parts; Competition 5-11. Be able to optimize a product for typical components or parts; Competition 5-12. Be able to perform three-dimensional modelling for typical components or parts; Competition 5-13. Be able to carry out three-dimensional assembly for typical components or parts; Competition 5-14. Be able to perform motion simulation animation and explosion animation for typical components or parts;	CAD Mechanical Design Competition Regulations

Subsequently, the core knowledge and skill-related points required for the X certificate in Industrial Robot Integration Applications, Programmable Controller System Applications, Machine Vision System Applications, Motion Control System Development and Applications, and for the Draftsman Vocational Skill Level Certificates, Electrician Vocational Skill Level Certificates, and other relevant areas were systematically arranged and analyzed to establish the “X Certificate” knowledge and skill-related point analysis table for the mechatronics technology profession, as illustrated in Table 2 (taking the industrial robot integration application X certificate as an example).

Table 2. “X Certificate” knowledge and skill-related point analysis table

Certificate Name	Core Knowledge and Skill-related Points	References
Industrial Robot Integration Applications	Certificate 1-1. Be able to read and understand the system integration programme manual; Certificate 1-2. Be able to read and understand the system integration operation manual; Certificate 1-3. Be able to read and understand the system integration maintenance manual; Certificate 1-4. Be able to complete the assembly and adjustment of the mechanical parts of the system according to the specification of the mechanical assembly drawings; Certificate 1-5. Be able to complete the assembly and adjustment of the pneumatic part of the system tuning according to the specification for pneumatic schematic; Certificate 1-6. Be able to complete the assembly and adjustment of the electrical part of the system according to the specification for electrical schematic; Certificate 1-7. Be able to develop simple system integration programmes according to production tasks; Certificate 1-8. Be able to perform common equipment selection based on production tasks; Certificate 1-9. Be able to perform 3D modelling based on production tasks; Certificate 1-10. Be able to construct virtual integration systems based on production tasks; Certificate 1-11. Be able to perform robot production line process flow planning; Certificate 1-12. Be able to perform virtual commissioning and beat optimization of a robot production line; Certificate 1-13. Be able to perform advanced programming of robots and peripheral equipment, etc.; Certificate 1-14. Be able to develop a variety of integrated applications such as product processing and manufacturing, handling and assembly according to production tasks.	Vocational Skill Level Standard for Industrial Robot Integration and Application

Finally, the core knowledge and skill-related points, as outlined in the Analysis Table of Knowledge and Skill-related Points in the “Skill Competition” and “X Certificate” Knowledge and Skill Point Analysis Table of Mechatronics Technology Profession, will be incorporated into the existing curriculum system, thus establishing the Comparison Table for Integrating Knowledge and Skill-related Points of “Competition” and “Certificate” into the Curriculum of mechatronics technology profession. The core knowledge and Skill-related Points will be integrated into the original curriculum system, forming a comparison table of the knowledge and Skill-related Points integrated into the curriculum of electromechanical integration technology, as shown in Table 3 (taking the Electricity and Electronics Technology course as an example). In instances where the pertinent knowledge and skill-related points cannot be incorporated into the existing curriculum, consideration may be given to undertaking this as professional elective courses or professional development courses. As per the Comparison Table for Integrating Knowledge and Skill-related Points of "Competition" and "Certificate" into the Curriculum of mechatronics technology profession, there is a necessity to optimize the standard of the professional curriculum, and improve the teaching materials such as lecture plans and teaching plans.

Table 3. Comparison Table for Integrating Knowledge and Skill-related Points of "Competition" and "Certificate" into the Curriculum

Integration into the Curriculum	Knowledge and Skill-related Points of "Competition"	Knowledge and Skill-related Points of "Certificate"
Electrical and electronic technology	Competition 1-18. Be able to select correct components such as relays, contactors, switches and buttons, and pneumatic components; Competition 1-25. Be able to select electrical and electronic components; Competition 4-1. Be able to select the correct components based on task requirements; Competition 4-12. Be able to analyze device faults according to the problem and detect the quality of the device; Certificate 4-4. Familiar with all kinds of common sensors and be able to select, install and apply them;	Certificate 6-3. Master the principle of arc extinguishing and common methods, master the structure and working principle of vacuum high-voltage circuit breaker and the protection device thereof; Certificate 6-4. Master the principle of differential protection and high-voltage leakage protection devices, understand the types and hazards of over-voltage and the characteristics of insulating media, master the structure and working principle of the high-voltage bridge and testing transformer; Certificate 6-5. Master NAND circuits, logic algebra and simplification, truth tables, drive equations for JK and D flip flops, state transition diagrams for decimal and octal counters, truth tables, and oscillograph;

4.2 Practice the "three-stage, multi-facility, and three-cycle" educational model

Figure 2 illustrates the "three-phase, multi-facility, three-cycle" educational model, oriented towards the demand for "post-course-competition-certificate". The entire learning process is divided into three phases: basic competence training, special competence training and comprehensive competence training. The initial phase, designated as basic competence training, corresponds to the first academic year. This phase is predominantly characterized by theoretical instruction in the classroom and practical training in the training room, which aims to ensure the learning and mastering of fundamental knowledge. In the subsequent academic year, the focus shifts to honing special competencies, characterized by an emphasis on "competition" and the acquisition of recognized credentials. This phase entails a spiral cycle of training, competing and assessment, encompassing various settings such as the training room, the skills competition venue, and the X certificate vocational skill appraisal examination room. This cycle is designed to facilitate the refinement and mastery of the professional core abilities. The stage of comprehensive competence training is primarily aligned with the third academic year, with an emphasis on cultivating "post" comprehensive ability. Students are expected to rotate between workshops and offices. In the fifth semester, the programme simulates actual enterprise production, aligning with enterprise positions, and encompasses five production training projects such as mechanical product design and processing, intelligent production line assembly, operation and maintenance. In accordance with the results of the skill competition, X certificate examinations, and interests and hobbies, students select one of the above five projects. They are then trained in different directions and positions. In the sixth semester, the students complete actual production projects in enterprises through a dual tutor-led and student-centered approach, which is a modern apprenticeship work-learning mode.

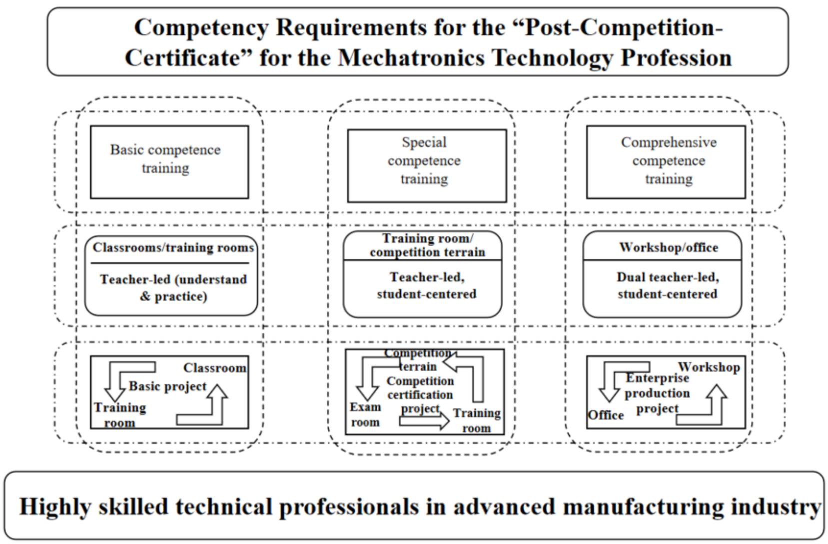

Figure 2. "Three-stage, multi-facility, and three-cycle" educational model

4.3 Construct an evaluation system that integrating "post-course-competition-certificate"

The curriculum system, as it pertains to the integration of "post-course-competition-certificate", involves numerous factors, including post, course, skill competition and industry certificate. It is imperative to incorporate the elements of post assessment, skill competition results and industry certificate assessment results into the evaluation system. The integrated "post-course-competition-certificate" personnel training mode has been implemented in our school's mechatronics technology profession. A joint evaluation of personnel training quality has been introduced via "course teaching-skill competition-industry certification-enterprise evaluation". Furthermore, a personnel training evaluation system has been constructed, guided by the achievements of the "post-course-competition-certificate" paradigm. The evaluation results are then used to identify and address any issues that arise in the personnel training process, ensuring a dynamic and cyclically adjusted personnel training mode. The evaluation system that integrates the "post-course-competition-certificate", is illustrated in Table 4.

Table 4. Comprehensive evaluation system of students' academic performance that integrates "post-course-competition-certificate"

Indicators	Connotation of Indicators	Calculation Method of Score	Scoring Basis
Job practice (15%)	Examine students' comprehensive practical abilities such as professional knowledge, professional skills and vocational qualities.	1. If the grade given in the internship evaluation form is a specific mark, that mark will be counted directly; 2. If the internship evaluation form is based on a grading system, 100 points will be awarded for excellence, 85 points for good, 75 points for average, 60 points for pass, and 0 points for fail.	Evaluation scores of enterprise masters in the internship appraisal form
Course grades (55%)	Examine students' mastery of public courses, basic professional courses, professional skills courses, etc.	Average score of all course grades on transcript.	Transcripts exported from the academic affairs system
Competition results (15%)	Examine students' professional expertise in a certain area or certain aspects.	1. 100 points for winning the first prize at either the national or provincial level. 2. 90 points for the second prize and 80 points for the third prize in provincial competitions 3. 90, 80 and 70 points for the first, second and third prizes in municipal competitions respectively. 4. 80, 70 and 60 points for the first, second and third prizes in school-level competitions respectively.	Skills competition award certificates or public documents
Examination performance (15%)	Examine the mastery of vocational competence in a type or certain types of work corresponding to the students' professional positions	1. 100 points for obtaining 1 vocational skill level certificate (senior and above); 2. 80 points for obtaining 1 vocational skill level certificate (intermediate); 3. 60 points for obtaining 1 vocational skill level certificate (junior).	Vocational skill level certificate

5 Difficulties and solutions in the process of "post - course - competition – certificate" integration practice

5.1 Deepen the integration of industry and education based on the "post"

Vocational education has a fundamental role to play in equipping individuals with the necessary skills to support industrial and enterprise development, so it is crucial to carry out deep integration of industry and education. However, enterprises often neglect their responsibilities for the integration of industry and education due to difficulties in retaining personnel. In order to realize in-depth industry-education integration, it is necessary to solve the dilemma of "retention difficulty". To address this challenge, our school has initiated a series of practices, yielding notable outcomes. Firstly, in collaboration with enterprises, our school has established an intelligent manufacturing industry college. Each enterprise is expected to contribute 1-2 technical personnel as part-time faculty members on a semester basis, who are tasked with imparting students' understanding of the enterprise. Secondly, enterprises participate in skill competitions on campus in the capacity of sponsors, and the school and enterprises collaborate in the formulation of test questions, the organization of competitions, and the award of certificates, with a view to fostering stronger ties between students and enterprises. Finally, in the fifth semester of the "three-stage, multi-facility, and three-cycle" educational model, the actual production of enterprises is simulated, with the students docking with the positions of enterprises and carrying out five production training projects, such as mechanical product design and processing, intelligent production line assembly, operation and maintenance etc. Each enterprise is assigned one of these projects, and students select their preferred project based on a variety of criteria, including their skill competition results, X-certificate examinations, and personal interests. The training is diversified, with students being instructed in different directions and positions, with a view to decreasing the likelihood of frequent job-hopping after graduation.

5.2 "Strengthen teacher team building with the aid of "competition and certificate"

A comparison of the traditional personnel training mode with the personnel training mode under the integration of the "post-course-competition-certificate" reveals that the latter puts forward more and higher requirements for the teacher team. The success of the implementation of the personnel training mode under the integration of the "post-course-competition-certificate" is contingent upon the capacity to establish a high-quality and high-efficiency teacher team. Our mechatronics technology profession is structured into three specialization tracks, namely mechanical design and manufacturing, automatic production line assembly, and mechanical and electrical equipment maintenance based on courses, skill competitions, and skill certification projects. Each team is overseen by a highly qualified and educated teacher, such as a doctor or a professor, and its members consist of backbone teachers, newly qualified teachers, and teaching assistants. The team leader is responsible for the macro coordination of the work of the whole team, while the backbone teachers are tasked with the implementation of specific team affairs in accordance with the arrangements of the team leader. The newly qualified teachers provide assistance to the backbone teachers in carrying out their responsibilities, and the teaching assistant assist in completing the venue set up, accounting and other logistical work. The team is composed of teachers from different levels and with distinct specialisms, thus ensuring that the team is divided into clearly defined roles, thereby mitigating the issue of teachers facing challenges independently.

5.3 Performance guarantee to optimize and improve institutional construction

In the personnel training mode that integrates "post-course-competition-certificate", teachers are obligated to engage in skill competitions and skill certification concurrently with classroom teaching. Consequently, their workload has increased substantially. Therefore, it is imperative to further refine and enhance the performance guarantee system to achieve "distribution according to work" and expand the scope of workload accounting to fully stimulate the enthusiasm of teachers and students. In terms of teaching faculty, our school has introduced a revised approach to the management of skill competitions and the accounting of workloads. The revised approach has resulted in an enhancement of the compensation for teachers, with their remuneration now being increased to 1.5-2 times the original amount. Concurrently, the school has instituted a new policy that considers the participation in skill certifications and competitions as a critical component of the evaluation of their merits and titles, which has led to a marked increase in teachers' enthusiasm for participation. Conversely, students are encouraged and supported from a range of perspectives, including recognition through awards (certificates), credit exchange, second classroom results, and favorable consideration in various merit assessments, thus fostering their voluntary and active engagement in skill competitions and skill certification.

6 Practical effectiveness of "Post-Course-Competition-Certificate" Integration

The employment rates of graduates of mechatronics technology major in the past five generations are 82%, 90%, 94%, 99%, and 100%, respectively. The employment rate has been increasing year by year, and the employment rate of the 2023 graduates has reached 100%. The trend change chart of employment rate is shown in Figure 3. The monthly salaries of the last five graduates are 4006 CNY, 4534 CNY, 4779 CNY, 5119 CNY, and 5437 CNY, respectively. The average monthly salary is 4775 CNY, which is 6.91% higher than the national average monthly salary of 4466.2 CNY in vocational colleges. The Comparison of Monthly Salary of Graduates is shown in Figure 4. The professional matching rates of the past five graduates are 66%, 60%, 82%, 60%, and 73%, respectively. The average matching rate is 68.2%, which is 8.95% higher than that of the national average. (The data is sourced from the MyCOS Report）

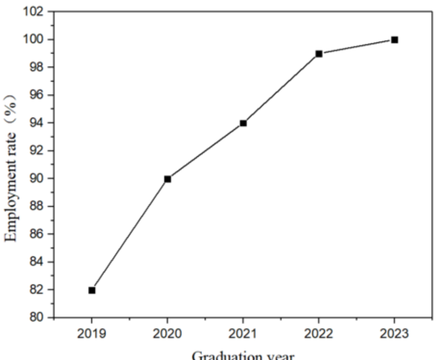

Figure 3. The trend in the employment rate of graduates

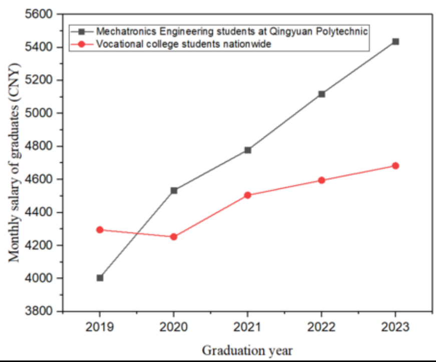

Figure 4. Comparison of Monthly Salary of Graduates

7 Conclusion

The integration of "post-course-competition-certificate" represents a significant initiative within the context of vocational education reform. This paper employs the Mechatronics Technology Profession of Qingyuan Polytechnic as a case study to explore and discuss the practical implementation of this integration and has achieved certain results. However, the exploration of personnel training modes for the "post-course-competition-certificate" integration remains a continuous process of optimization and refinement. Notwithstanding, numerous issues persist, including an overreliance on competitive equipment in provincial and above-level skill competitions for engineering majors, the fairness of competitions, and the excessive number of categories of vocational skill level X certificates. In the future, we will continue to explore the integrated education model of "Post-Course-Competition-Certificate" from the following aspects:

a. Continue to deepen the integration of industry and education through initiatives such as industry-academy colleges, industry-education alliances, and mobile enterprise workspaces, thereby enhancing the alignment between talent cultivation and corporate needs.

b. Regularly conduct job research in enterprises and sort out changes in skills competitions and certification projects, optimizing the established curriculum standards of “post-course-competition-certificate” integration.

c. By optimizing and improving the incentive mechanism, we can further enhance the enthusiasm of teachers and students to participate in the integration practice of "Post-Course-Competition-Certificate".

Fund Project

“Exploration and Practice of Educational Mode That Integrates “Post – Course – Competition - Certificate” in Mechatronics Technology Profession of Higher Vocational College”, Teaching Reform Project of Qingyuan Polytechnic (JG23005); “Construction of Microcontroller Simulation Project Library Based on Engineering Practice”, Teaching Reform Project of Department of Education of Guangdong Province (GDJG2021375); “Construction and Research of Textbooks Based on New Forms of Blended Teaching - Taking Motor and Electrical Control Technology as an Example”, Qingyuan City Educational Research Project (23-115);Teaching Research Project of Qingyuan City (21-96).

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Research Progress and Development Trend Analysis of Domestic and Foreign Enterprise Technological Innovation Based on Bibliometrics

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Abstract. In the current world situation, enterprises have unique technological innovation means in order to gain cutting-edge advantages in fierce competition and promote sustainable development. Enterprise technological innovation is an important way to influence regional and global innovation development, and a key source of cutting-edge innovation. Enterprise technological innovation has received widespread attention from scholars and the market, and related research has become a hot trend in the field of enterprise and technological development research. As a supplement to the qualitative review of research on technological innovation in existing enterprises, based on the retrieval of relevant literature from two major domestic and foreign literature databases (Web of Science database and CNKI database), CiteSpace scientific software was used to visually analyze the Chinese and English literature related to technological innovation research in domestic and foreign enterprises from 1993 to 2023. Through bibliometric and knowledge spectrum analysis methods, the basic research status of the country distribution, institution distribution, author distribution, and keyword clustering of literature in the field of technological innovation in domestic and foreign enterprises in the past thirty years was sorted out. The domestic and foreign research development stages and future hot trends in this field were summarized, providing reference and future research development for improving the more efficient development of technological innovation and entrepreneurship in Chinese enterprises.

Keywords. Enterprise technological innovation; Literature search; Visual analysis; Development trend

1. Introduction

As the core entity of technological innovation and achievement transformation, enterprises serve as the key driver for regional economic upgrading and national competitiveness enhancement. Large European and American corporations have propelled global industrial advancement through technological breakthroughs, demonstrating the pivotal role of enterprises in innovation ecosystems. Amid shifting

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global dynamics, the urgency to overcome “bottleneck technologies” and achieve scientific autonomy underscores the strategic imperative of reinforcing enterprises’ innovation leadership. Technological innovation not only boosts corporate efficiency and scale but also drives trade growth, regional industrial synergy, and employment stability through spillover effects, fostering socio-economic sustainability. China’s 2015 “mass entrepreneurship and innovation” policy ignited grassroots creativity, accelerated resource integration, and established a collaborative “government-industry-academia-application” ecosystem, injecting sustained momentum into innovation-driven development [1, 2]. In technological innovation, enterprises serve as the core investment entities, responsible for coordinating both funding and talent allocation. They act not only as fundraisers but also as managers and utilizers of innovation capital, while talent investment should focus on systematic team-building rather than individual researchers, enhancing innovation efficiency through optimized talent structures. Scientific innovation is characterized by high investment and risk, yet under China’s current system, governments and research institutions bear partial risks, hindering the full establishment of enterprises as the core innovation entities. Challenges such as delayed commercialization of technological achievements and market disconnection have dampened corporate innovation incentives. Reconstructing the innovation ecosystem requires balancing government, market, and societal roles, addressing market and government failures, and solidifying enterprises’ position as the primary innovators. Driven by both market demand and national strategies, this approach will propel technological leapfrog development and comprehensively elevate China’s innovation capacity.

Current research on enterprise technological innovation globally revolves around three dimensions: policy environment, enterprise capabilities, and individual innovators. Policy studies emphasize national incentives like subsidies and tax benefits driving R&D investment. Enterprise-level analyses highlight resource constraints in SMEs necessitating collaborative innovation, while large firms leverage high R&D expenditure for breakthroughs [3, 4]. Individual-focused studies explore traits of innovators and industry-academia collaboration, exemplified by Huawei and Alibaba DAMO Academy’s open ecosystems attracting top talent. Empirical findings reveal: Hilmersson et al. [5] found SMEs’ innovation pace accelerates international expansion, though founding time weakens this effect; Ndzana et al. [6] demonstrated via PSM that integrating technical and non-technical innovation enhances performance; Huy-Cuong’s Vietnam data showed R&D investment and formal training drive innovation, while financial/policy barriers shape activity choices [7]. These studies unveil complex interactions among multidimensional factors, offering theoretical foundations for policy making and corporate strategies. Existing studies on enterprise technological innovation lack systematic cross-country comparisons and dynamic evolution analysis [8]. Amid global geopolitical shifts, knowledge graph-based quantitative bibliometrics (e.g., U.S. dominance in core AI patents vs. China’s application-layer focus) can reveal transnational innovation patterns, offering visual analytics to advance theoretical frameworks and policy alignment.

To systematically map the research landscape of enterprise technological innovation across global and domestic contexts, this study employs bibliometric analysis and the visualization tool CiteSpace. Building on prior research, we systematically analyze literature from the Web of Science (WOS) Core Collection and China National

Knowledge Infrastructure (CNKI) databases. The analysis examines fundamental characteristics such as country distribution, institutional collaboration, keyword co-occurrence, and burst detection in academic publications from 1993 to 2023. This approach reveals the evolution of research themes, highlights cross-regional disparities (e.g., Western focus on innovation ecosystems vs. China's policy-driven models), and identifies theoretical frontiers. The findings provide a data-driven framework for advancing research and informing evidence-based policy making, contributing to both theoretical and practical advancements in enterprise innovation studies.

2. Research Methods and Data Sources

With the advancement of global technology, the hotspots and priorities of scientific research evolve dynamically. These shifts can be analyzed by examining publicly available literature through systematic approaches. Bibliometrics, as a discipline, applies mathematical and statistical principles to quantitatively describe and analyze the quantity, structure, and evolution of scholarly publications. It enables the identification of disciplinary development patterns, prediction of research trends, and revelation of evolutionary mechanisms underlying scientific activities. This methodology provides evidence-based support for scientific management and policy-making, offering critical insights into the growth dynamics and future directions of academic fields.

CiteSpace is a scientific knowledge mapping tool based on dynamic network theory. Built on the Java programming language, it enables structural, trend, and evolutionary analysis within scientific fields through bibliometric methods. By processing domain-specific literature, the tool visualizes research paradigms and developmental trajectories of disciplines, aiding in the identification of emerging trends, key contributors, and intellectual dynamics in academic domains [9, 10].

This study constructed a bibliometric database focused on enterprise technological innovation. For English literature, 1,423 SSCI articles (1993-2023) were initially retrieved from Web of Science using keywords like "Enterprise technological innovation," followed by manual screening and supplementary searches in authoritative journals, resulting in 661 refined papers. Chinese literature was sourced from CNKI with keywords "Enterprise technological innovation" and "Technological innovation" filtered by Peking University Core Journals and CSSCI standards, yielding 488 articles after removing irrelevant entries. All abstracts and keywords were formatted per CiteSpace requirements to build the data pool for subsequent knowledge mapping and trend analysis.

3. Visualization Analysis of Technological Innovation in Global and Domestic Enterprise

3.1 Annual and Quantitative Distribution

Analysis of annual publication trends from 1993 to 2023 (Figure 1) reveals a sustained growth in corporate technological innovation research. Before 2000, global publications remained sparse, with fewer than 10 articles annually. Rapid expansion began post-2001, surging after 2010 and peaking at 154 articles in 2023, marking a 48.1% increase from 2022. Domestically, research initially paralleled international efforts, dominating 68.8% of total publications in 2001 and maintaining leadership until 2016 (except 2011), aligned with China's innovation-promoting policies. However, domestic output declined post-2017, plummeting to 12 articles in 2023, while international publications surged to 142. This divergence reflects China's academic evaluation policies incentivizing researchers to prioritize international journals, significantly reducing domestic contributions.

Analysis of the publication volume on enterprise technological innovation from 1993 to 2023 indicates that this field has become a focal point in technological innovation research, drawing significant attention from scholars and industry practitioners. However, a notable disparity exists between domestic and international publication outputs. A systematic synthesis of global and local research hotspots is imperative to align with cutting-edge trends, uncover emerging topics, and provide actionable insights for Chinese researchers to publish high-quality studies in this domain.

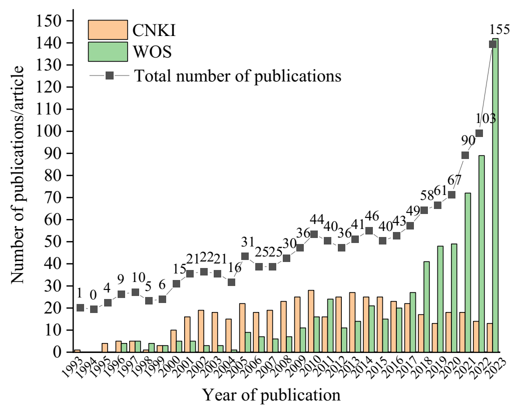

Figure 1. The number and trend chart of published papers on enterprise technological innovation research in domestic and foreign journals from 1993 to 2023.

3.2 Country/Region Distribution

National political-economic environments and policy frameworks critically shape enterprise technological innovation research trends. Bibliometric analysis via CiteSpace reveals China's dominance with 316 publications (47.73% of global output) and the highest centrality (0.83), while the U.S. (76 articles) and U.K. (73 articles) follow (Table 1). Europe collectively contributes 194 papers, reflecting regional collaboration, and Asia shows vitality in China, South Korea, and India. Despite China's later entry, its ascendancy stems from two drivers: policy ecosystems—post-reform legal frameworks, incubators, and tax incentives fostering innovation—and industry-academia synergy—exemplified by Huawei and Tencent's alliances with universities to commercialize research. Europe sustains activity through corporate diversity, while the U.S. leverages capital and regulatory agility. The study underscores that stable governance, legal enforcement, and resource integration define a nation's innovation research leadership, with China’s model offering a “policy-industry-academia” paradigm for emerging economies [6, 11].

Bibliometric research employs tools like CiteSpace to visualize collaboration networks, revealing patterns and trends. Author co-occurrence maps identify core research groups. This study analyzes collaboration dynamics in enterprise technological innovation using CNKI and WOS data, decoding academic synergy evolution.

Table 1. Distribution of enterprise technological innovation research in countries/regions and institutions worldwide.

Ranking	Country/Region	Quantity/article	Percentage/%	Centrality	Year of first publication
1	China	316	47.73	0.83	1998
2	America	76	11.48	0.35	2000
3	Britain	73	11.02	0.43	1997
4	Italy	51	7.70	0.34	2002
5	Spain	36	5.44	0.18	2008
6	France	26	3.93	0.13	1996
7	Australia	21	3.17	0.08	1999
8	Republic of Korea	21	3.17	0.06	2014
9	Germany	18	2.72	0.10	2005
10	Canada	17	2.57	0.05	2001
11	India	16	2.42	0.07	2000

3.3 Analysis of literature keyword

Keyword co-occurrence maps via CiteSpace reveal “performance” and “innovation” as core high-frequency nodes in global enterprise technological innovation research, forming dense network structures (Figure 2a). The tight linkage between innovation and corporate performance underscores its role as a key growth metric. Robust connections among high-frequency terms and minimal isolated nodes validate the systematic theoretical framework, spanning R&D, management, and marketization, demonstrating innovation's holistic impact on enterprise development.

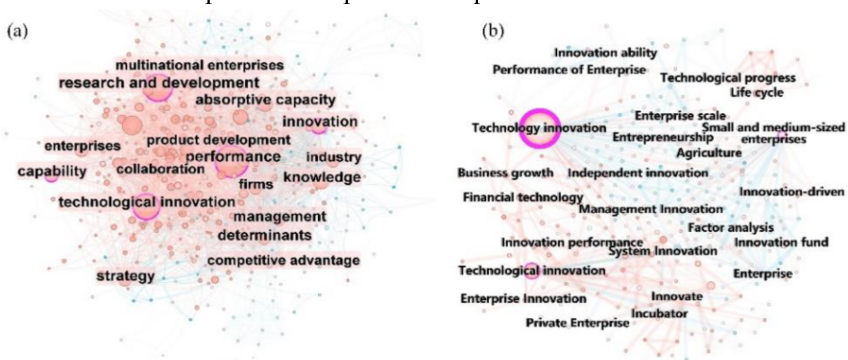

Figure 2. Co-occurrence map of keywords related to enterprise technological innovation research in international (a) and Chinese (b) journals from 1993 to 2023.

The co-occurrence map of Chinese journals (Figure 2b) highlights “technological innovation", "scientific innovation", and "SMEs" as core nodes with high centrality. However, numerous isolated nodes and sparse connections between high/low-frequency terms indicate fragmented themes. While a foundational framework has emerged, systematic integration remains under development, underscoring the need for broader theoretical scope and interdisciplinary synergy in domestic research.

Bibliometric analysis via CiteSpace reveals high-frequency keywords in global enterprise technological innovation research (≥23 occurrences) cluster into three themes, which are innovation performance (efficacy evaluation and competitive enhancement), R&D dynamics (knowledge spillovers and empirical modeling), and production innovation (process optimization and smart manufacturing), reflecting a focus on quantifiable outcomes (Table 2). In contrast, Chinese studies prioritize institutional innovation, private enterprises, and collaborative innovation, emphasizing policy integration and localized practices, yet lack systemic theoretical frameworks compared to international research (Table 3).

Table 2. High frequency keywords for research on technological innovation in foreign journal enterprises.

Keyword	Frequency	Centrality	Keyword	Frequency	Centrality
Performance	191	0.12	Enterprise	36	0.05
Research and development	180	0.11	Determinants	36	0.10
Technological innovation	146	0.12	Industry	35	0.05
Innovation	83	0.12	Technology	34	0.05
Impact	82	0.03	Dynamic capacity	32	0.01
Firms	76	0.05	Foreign direct-investment	28	0.03
Absorptive-capacity	70	0.09	Multinational-enterprises	28	0.04
Growth	65	0.03	Firm	27	0.05
Knowledge	59	0.09	Collaboration	27	0.06
Strategy	57	0.06	Investment	26	0.03
Firm performance	54	0.04	Empirical evidence	26	0.03
Capacity	49	0.12	Innovation performance	25	0.01
Product innovation	47	0.05	Spillovers	25	0.04
Management	44	0.09	Product development	25	0.07
Productivity	38	0.00	Business	24	0.04

Chinese research on enterprise technological innovation centers on three themes: "technology innovation", "SMEs" and "scientific innovation". High-frequency terms like "collaborative innovation" reflect SMEs' reliance on regional partnerships to mitigate risks due to limited independent R&D capacity. Keywords such as "innovation funds" highlight policy dependency for financial support. Compared to global studies, China's keyword frequency and diversity are lower, attributed to fewer publications and a policy-centric focus. While "technological innovation" is the sole overlapping top keyword internationally, foreign research emphasizes performance-R&D linkages, contrasting with China's policy-ecosystem priorities.

Table 3. High frequency keywords for research on technological innovation in domestic journal enterprises.

Keyword	Frequency	Centrality	Keyword	Frequency	Centrality
Technological innovation	169	0.78	Financial technology	7	0.04
Small and medium-sized enterprises	37	0.14	System innovation	6	0.01
Technology innovation	35	0.13	Technology finance	6	0.01
Enterprise	18	0.04	Incubator	6	0.01
Innovate	11	0.04	Innovation performance	6	0.03

Innovation ability	10	0.02	Cooperative innovation	5	0.02
Collaborative innovation	7	0.01	Efficiency	5	0.01
Innovation fund	7	0.02	Enterprise innovation	5	0.07

4. Research Evolution

Keyword burst analysis identifies sudden frequency shifts in thematic terms to reveal research trend evolution. From 1993 to 2023, international journals showed 13 bursts (Figure 3a), while Chinese journals had 12 (Figure 3b). Based on visual bibliometric analysis of international and domestic journals focusing on corporate technological innovation literature, this study identifies research priorities across different periods through high-frequency keywords. The analysis reveals distinct phases and research emphases in global and domestic academic circles. From 1993 to 2023, 13 burst keywords emerged in international journals, while 12 burst keywords were identified in domestic journals. The start and end years of these burst keywords in the detection graph indicate their sustained prominence as research hotspots during specific periods. The intensity metric reflects the citation frequency of each keyword, quantifying its academic influence. This temporal mapping demonstrates evolving research trends, with international studies showing longer burst durations (average 6.2 years) compared to domestic research (average 4.8 years). Key thematic shifts include early focus on innovation management (1990s), transitioning to open innovation (2000s), and recent emphasis on digital transformation and sustainability (post-2010s).

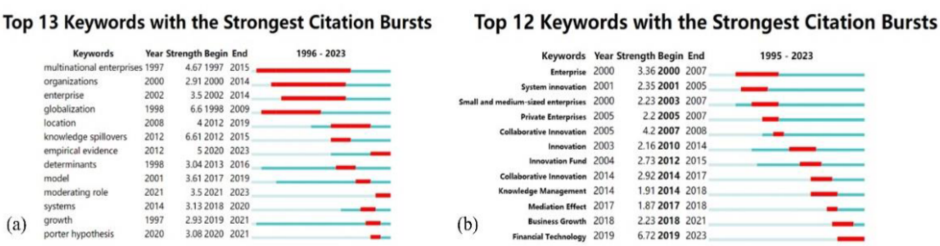

Figure 3. International (a) and Chinese journal (b) keyword emergence chart from 1993 to 2023.

4.1 Evolution of Research Abroad

Based on CiteSpace keyword burst detection and bibliometric analysis, international research on corporate technological innovation can be divided into three phases. The first stage is the Initial Stage (pre-2001). Studies in this period focused on the foundational role of technological innovation in multinational enterprises under globalization, with core themes including “multinational enterprises”, “globalization” and “organization”. Despite limited publications, this phase established innovation as a key driver for efficiency enhancement, cost reduction, and global competitiveness, particularly in resource allocation and production optimization. Then, the following stage is the Steady Development Phase (2001-2016). Research shifted toward systematic analysis with keywords like “knowledge spillovers”, “empirical evidence” and “systems”. The *Porter Hypothesis* emerged as a central framework, positing that well-designed environmental regulations stimulate innovation rather than hinder competitiveness. Empirical studies confirmed the positive correlation between stringent policies and corporate R&D investments, laying groundwork for dynamic cost-offset models. After 2016 (Rapid Expansion Phase), investigations were deepened into regulatory mechanisms and interdisciplinary integration, highlighted by keywords “moderating role” and “*Porter Hypothesis*”. The dynamic interplay between environmental regulations and green innovation became pivotal, demonstrating how compliance costs could be offset through eco-efficient technologies. Concurrently, the significant contribution of Chinese scholars in international journals reflect domestic policy emphasis on sustainable innovation, showcasing a blend of global collaboration and localized practices.

4.2 Evolution of Domestic Research

Due to the relatively small number of published papers in China compared to foreign countries, the emerging keywords continue to focus on individual research topics. Therefore, the author combines manual sorting and discrimination to divide the research on technological innovation in domestic enterprises into the following three stages.

- Conceptual Exploration Phase (pre-2000): Driven by post-WTO accession policies, early studies focused on state-owned enterprises, emphasizing the strategic role of innovation but lacking empirical data.
- Steady Development Phase (2000-2007): Rapid growth in enterprise numbers and market reforms spurred increased publications. Keywords like “institutional innovation” and “private enterprises” highlighted localized policy integration and collaborative innovation practices.
- Transition Phase (after 2007): Research shifted toward systemic models, integrating global theories with Chinese contexts. Keywords such as “knowledge management” and “fintech” indicated deeper analytical focus. While Chinese scholars prioritized international journals for cross-border validation, domestic journals faced challenges in theoretical cohesion.

5. Conclusions and Research Prospect

Studies on enterprise technological innovation emerged simultaneously worldwide. While Chinese publications dominated international journals from 2001-2016, foreign outputs surged thereafter. Half of global contributions involve Chinese authors, yet systematic collaboration among core scholars remains limited. International journals exhibit broader systemic insights due to cross-border academic exchanges and localized theoretical adaptations. In contrast, domestic studies in Chinese journals are fragmented, lacking cohesive theoretical frameworks. Early Chinese research focused on qualitative case studies but shifted to quantitative methods with increased global engagement. Despite declining domestic outputs due to overseas publication preferences, recent policy support highlights potential for developing China-specific innovation theories.

Future studies should focus on optimizing incentive models and performance evaluation systems for enterprises of varying scales, balancing R&D input-output efficiency, and mitigating risks to achieve sustainable development. Ecosystem-Based Systemic Research: Innovation research must shift from linear approaches to dynamic, multi-level ecosystems involving enterprises, universities, governments, and financial institutions. Emphasis should be placed on localized applications to adapt to complex socio-economic environments. Talent-centric innovation is critical. Systematic studies are needed on how education, corporate practices, and policy incentives synergize to cultivate innovation capabilities at individual and team levels. Last but not the least, investigating causes of innovation failures (e.g., funding gaps, market misalignment) across development stages will enhance enterprises' adaptive capacity and competitiveness.

Acknowledgments

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Modern Management based on Big Data VI
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Research on Foreign Language "Dual Teacher" Development in Yangtze River Delta Region Vocational Colleges

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Abstract. This study investigates challenges in developing foreign language 'dual teacher' teams in Yangtze River Delta vocational colleges, using survey data from 186 teachers. Results reveal gaps in teacher morality, practical teaching skills, and enterprise collaboration. Policy recommendations include strengthening incentive mechanisms, optimizing training, and deepening college-enterprise partnerships.

Keywords. Dual teacher, integration of industry and education, Vocational foreign language teacher team

1. Introduction

In the context of the vigorous development of vocational education, the construction of a "dual teacher" teaching team has become a core element in improving the quality of vocational education [1]. As the forefront of China's economic development, the development of vocational education in the Yangtze River Delta region is of great significance in promoting regional industrial upgrading and economic transformation. Compared with Germany's dual vocational system, double qualified teachers in our country not only need to possess solid professional theoretical knowledge, but also need to have rich practical experience and proficient professional skills. They should be able to integrate the latest industry trends and practical operational experience into the teaching process, and cultivate high-quality technical and skilled talents that meet market demand. In order to gain a comprehensive understanding of the actual situation of the construction of the foreign language"dual teacher" team in vocational colleges in the Yangtze River Delta region, we have carefully designed and conducted the questionnaire. Through in-depth analysis of the survey data, we hope to accurately grasp the current situation, identify existing problems, and propose practical and feasible targeted suggestions.

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2. Research Design

At present, the domestic academic community has achieved certain results in the construction of a vocational education "dual teacher" team. According to the search results of China CNKI (see Figure 1), research results related to the integration of industry and education and the construction of a "dual teacher" team have shown a continuous fluctuation and upward trend since 2000, and reached its peak around 2020. This indicates that the Chinese Ministry of Education continues to pay attention to the construction of dual teacher teachers, especially with the release of a series of related documents that promote active attention from the academic community to this topic. Among them, teacher team construction, industry education integration, and school enterprise cooperation are all related hot topics.

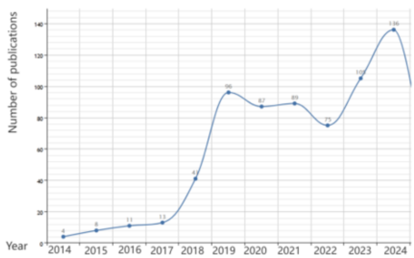

Figure 1. General research trend

2.1 Research Questions

This research mainly explores the following two questions:

(1) What are the core elements of becoming a foreign language 'dual teacher'?

(2) How can we construct a model to develop foreign language 'dual teacher' teams?

2.2 Research Subject

This survey is aimed at foreign language teachers and administrative staffs from vocational colleges, secondary vocational schools, and vocational undergraduate institutions in the Yangtze River Delta region. In the investigation process, we mainly use an online platform of Questionnaire Star to distribute questionnaires, striving to cover vocational colleges of different types and scales. After rigorous data screening and organization, 186 valid questionnaires are finally collected. The survey is comprehensive and detailed, covering multiple key aspects such as the quality, connotation, evaluation criteria, training mode, construction difficulties, and suggestions of "dual teacher". In order to fully collect various types of information, the questionnaire design adopts a combination of single choice, multiple choice, and free answer modes.

3. Research Results and Discussions

Based on the data and content of the questionnaire, carefully comparing the requirements of the "Basic Standards for 'Dual Type Teachers' in Vocational Education (Trial)" issued by the Ministry of Education in 2022 and the "Implementation Rules to Conduct the

Shanghai Municipal" Dual Type Teachers" Certification Work" issued by D Vocational College, this report comprehensively analyzes the current state on Foreign Language "Dual Teacher" Development in Yangtze River Delta Region Vocational Colleges. The report is on four dimensions from teacher morality, teaching ability, research and development achievements, to enterprise practice. The final feasible suggestions and opinions are proposed based on the overall research situation, common problems commonly existing in different types of colleges, and a few personalized problems.

3.1 Teaching Morality: Insufficient inner motivation for "dual teacher" professional development

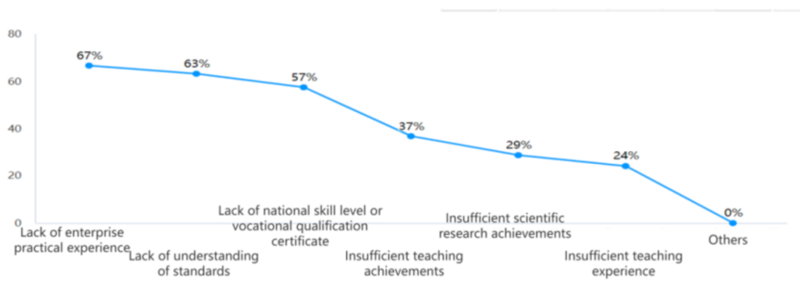

Figure 2. Reasons for low motivation in applying for "dual teacher"certificate

In practice, some teachers have low enthusiasm in applying for the "dual teacher" certification, mainly due to a lack of understanding of certification standards (63%), insufficient practical experience in enterprises (67%), as well as national skill level or vocational level certificates (57%), insufficient teaching achievements (37%), and other reasons (see Figure 2).

3.2 Teaching Competence:Difficulty in transformation between practical knowledge and teaching content

According to research results, the vast majority of teachers encounter problems such as lack of teaching method guidance (34.48%), limited time and energy (55.17%), and difficulty in systematically organizing practical knowledge (43.68%) when transforming practical knowledge into teaching content. The most important factor is that teachers themselves lack understanding or mastery of the latest technology applications in the industry (78.16%) (see Figure 3). This data indicates that vocational foreign language "dual teacher" in the Yangtze River Region often face insufficient abilities and methods in deconstructing cases and transferring knowledge during the process of knowledge transformation. Moreover, the daily teaching hours of vocational foreign language teachers are relatively long, making it difficult to guarantee the time in personalized teaching case development. Finally, foreign language teachers need a team to guide them in sorting practical knowledge system and teaching resource base.

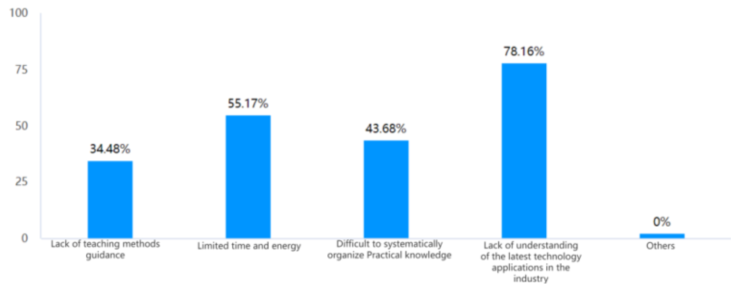

Figure 3. Difficulty in converting practical workplace content into teaching content

3.3 Professional Teaching and Research Achievements: Lack of training mechanism for "dual teacher"

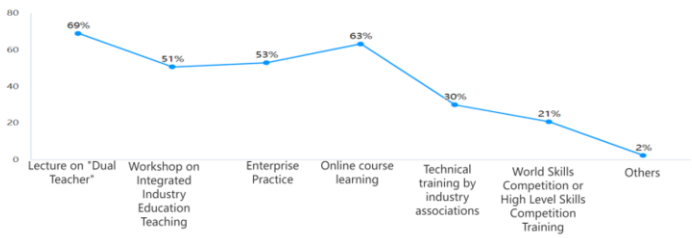

Figure 4. "Dual teacher" trainings for vocational college teachers

According to research results, most teachers have participated in lectures on themes of college-based "dual teacher" training (69%), teaching workshops on the integration of industry and education (51%), practical training in enterprises (53%), online course learning (63%), technical training for industry associations (30%), and training for world-class competitions or high-level competitions (21%) (see Figure 4). This indicates that most teachers participate sporadically in one or more training forms related to dual teacher training based on their own interests and a clear "dual teacher" training mechanism has not yet formed.

3.4 Enterprise Practice Experience: Lack of practical experience in enterprises

According to the questionnaire results (see Figure 5), in the past three years, most foreign language vocational college teachers have a relatively short period of time in participating in enterprise practice. For instance, 29.89% teachers have chosen 1-3 months. However, nearly 50% of teachers have hardly participated, which strongly affects their accumulation of practical experience in new technologies in enterprises and industries, and thus makes it difficult to combine practical cases in teaching, meanwhile indirectly affecting the effectiveness of vocational education teaching.

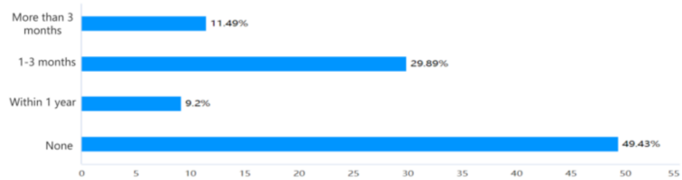

Figure 5. Average duration of vocational college teachers 'participation in enterprise

4. Implications and Suggestions for Foreign Language "Dual Teacher" Development

To build a high-level foreign language "dual teacher" teaching team for vocational education in the new era (see Figure 6), we need to combine key points. First, guided by the concept of standards, the first step is to prioritize moral character, strengthen political and professional ethics, and enhance the basic literacy of teachers. Secondly, we need to focus on professional teaching and enhance teaching skills. Thirdly, we need to have a sense of professional teaching and research, and solidly accumulate achievements. Finally, enterprise practice needs to be actively participated in to enhance the ability to transform achievements. Only by this way can we have connotation enhancement to realize the educational objectives of talent training quality.

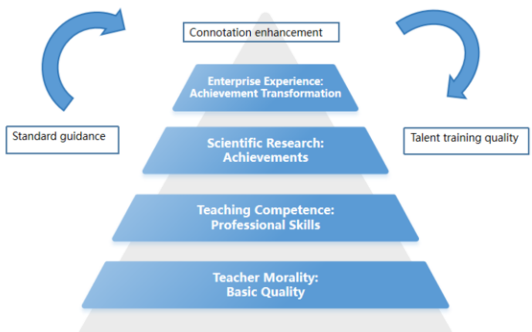

Figure 6. Practice path of foreign language "dual teacher" team

4.1 Strengthen Teacher Morality

4.1.1 Improve Incentive Mechanism

Vocational Colleges should establish a more comprehensive incentive mechanism, giving priority consideration and rewards to teachers who actively participate in the "dual teacher" training and achieve significant results in professional title evaluation, performance assessment, and excellence evaluation, fully mobilizing the enthusiasm and initiative of teachers [2-3]. Through the promotion of relevant policies and systems, it is clear that the construction of a "dual teacher" team is a requirement for the development of vocational education and an urgent need for future industrial upgrading, enhancing the professional identity and sense of belonging of foreign language dual teachers [4-5].

4.1.2 Refine the evaluation criteria to better align with industry needs

A scientific, reasonable, and diversified "dual teacher" evaluation system needs to be established. In the evaluation system, the weight of indicators such as practical ability and corporate performance should be significantly stressed, and more emphasis should be placed on teachers' performance and achievements in routine work [6-7]. For example, it is suggested to set up a dedicated practical ability assessment section, invite enterprise experts to participate in the evaluation, and conduct on-site assessments of teachers' English professional skills and problem-solving abilities. At the same time, the economic and social effects obtained by foreign language teachers participating in horizontal scientific research projects or enterprise practices should be included in the evaluation scope, and the "dual teacher" literacy level of teachers will be comprehensively and objectively evaluated. In addition, a systematic "dual teacher" career promotion and development plan should be provided to help foreign language teachers have a clear mind-map on their career development direction and enhance career development motivation [8].

4.2 Enhance Teaching Competence

4.2.1 Increase practical cases

Foreign language teachers should be encouraged to introduce more practical cases in their teaching, such as leading in typical application case analysis and thematic discussions of Vocational English Test System (VETS, which is a 1+X Practical English Communication Vocational Skills Certificate Examination), to cultivate students' thinking and analysis abilities and application innovation abilities in vocational English scenarios. In addition, foreign language teachers should actively explore college-enterprise cooperation, strengthen deep cooperation with language service enterprises, and jointly with enterprises develop customized courses such as "Translation Project Management", "Translation Technology and Information Retrieval", "Introduction to Machine Translation", "AI and Language Applications", relying on project-based teaching methods and modular teaching content to help students bridge the gap between English skills learning and practical application in workplace projects. In addition, foreign affairs service projects need to be actively introduced in teaching practice, such as international exhibition translation services, foreign affairs reception services, to enhance the practical English application ability. In response to the situation that foreign language teachers generally face a large number of class-teaching hours, it is possible to conduct the sorting of foreign language practical knowledge systems and the construction of resource bases.

4.2.2 Optimize training content

Based on teachers’ personalized needs, the training content for "dual teacher" should be optimized to ensure the effectiveness of the training content. For example, teachers can take VETS teacher training to greatly enhance the practicality of professional training content, through diverse training forms such as online, offline, and on-site observation, using methods such as visiting enterprises and researching industry technology development, accurately meeting the needs of enterprises, deepening the implementation of industry education integration, and improving the professional competence level. During the training process, teachers need to be arranged to visit relevant language-service enterprises for on-site visits and practical operations, to effectively integrate training content into the teaching process in the classroom [9]. In addition, we should actively organize skill competitions, industry enterprise competitions and expand industry skill certificate training, such as workplace English challenges and vocational English writing competitions, VETS certificate, human resources and social security e-commerce certificate, to enhance the links between teachers and language service enterprises, help foreign language teachers consolidate professional skills and techniques. Moreover, various artificial intelligence tools need to be used to enhance foreign language teachers' perception of the latest developments in the language service industry, and gradually improve their professional competence and qualities.

4.3 Promote Teaching and Research Achievements Transformation

4.3.1 Establish a mechanism for scientific research achievements transformation

Special funds at all levels need to be set up to support foreign language teachers in transforming scientific research achievements into practical teaching application content to improve the quality of vocational education teaching. For example, a research and innovation VETS team can be established to apply for "1+X" related teaching research and reform projects to accelerate scientific research results. In addition, we can build up interdisciplinary teaching teams according to the industry chain. For instance, we can combine emerging artificial intelligence and language service industries, say integrating foreign language teachers' translation technology with courses such as AI and language applications with natural language processing and computer software applications in the field of communication, working together to strive for research projects in related fields.

4.3.2 Innovate training mode of cultivating dual teachers

We should innovate the training mode of "dual teacher" team and carry out personalized, systematic and targeted training based on their different stages of professional development and skill levels. For instance, we can provide featured trainings from survival training that focuses on supplementing knowledge and technical weaknesses to developmental training that focuses on improving personalized abilities, or from comprehensive training that enhances the overall quality of teachers to specialized training that meets the personal professional development of teachers. Regarding the construction of a foreign language "dual teacher" team, vocational colleges can focus on the 1+X foreign language certificate examination and vigorously build a VETS evaluator team to enhance "dual teacher" quality of the foreign language teacher team. Finally, we need to further improve the teacher development mechanism and encourage the establishment of shared exemplary teacher development centers, such as relying on the 1+X exam and training, actively creating a 1+X practical English communication vocational skill level certificate model base, and forming a regional shared exemplary "dual teacher" training base.

4.4 Deepen enterprise practice

4.4.1 Strengthen college-enterprise cooperation from government side

The government should strengthen relevant policy support, increase funding for the construction of "dual teachers", establish special funds at all levels to support teacher training, enterprise practice, and the development of college-enterprise cooperation projects. By formulating tax preferential policies, certain tax reductions and exemptions will be given to enterprises actively participating in "dual teacher" training. At the same time, social honor awards should be established to recognize and promote enterprises that have made outstanding contributions in "dual teacher" training, and enhance the social reputation of the enterprises.

4.4.2 Deepen the integration of industry and education from college side

Colleges should actively establish close cooperative relationships with enterprises of language service, foreign affairs service, foreign trade, and enhance the language application and technical practice ability of foreign language teachers through college-enterprise cooperation projects, industry university research combination and other methods. At the same time, we need to increase the duration of foreign language teachers' off the job practice in enterprises, and encourage teachers to participate in the actual project management and operation of enterprises [10]. For example, college-enterprise cooperation can jointly establish a "dual teacher" practice base, enabling teachers deeply to participate in the product service process of language services and foreign affairs services, such as accepting and disassembling tasks, project management, project delivery, to ensure that enterprise practice teachers can participate in core technologies and important work processes, and effectively enhance the professional technical abilities and practical effects of foreign language teachers.

4.4.3 Build a collaborative community between colleges and enterprises

Colleges should concentrate scientific research teams to actively cooperate with enterprises. Based on enterprise needs, colleges and enterprise experts jointly take research, tackle enterprise technical problems, enhance enterprise technological competitiveness, improve social service capabilities and social influence of colleges, and form a community of shared interests between colleges and enterprises. In addition, in terms of policy-making and optimizing, both colleges and enterprises should strengthen communication and trust, establish a sound confidentiality mechanism, eliminate enterprises' concerns about the leakage of commercial secrets, and achieve a good status of win-win between colleges and enterprises.

4. Conclusion

This research, through comprehensive and in-depth data collection and analysis, clearly reveals the achievements and problems in the construction of "dual teacher" teams in vocational colleges in the Yangtze River Delta region. Although there is a certain consensus among vocational college teachers in terms of their understanding of the "dual teacher" quality and connotation, there are still many urgent problems to be solved in terms of evaluation standards, training models, and construction difficulties.

Through a series of practical measures such as improving the "dual teacher" evaluation criteria, innovating the "dual teacher" training model, strengthening policy support, and increasing the participation of language service and foreign affairs service enterprises, we have reason to believe that the construction of the foreign language "dual teacher" team in vocational colleges in the Yangtze River Delta region will be further strengthened, effectively improving the quality of vocational education and continuously supplying high-quality technical and skilled talents for the high-quality development of the regional economy. Only through multidimensional and systematic paths and solutions, with the cooperation of all levels and departments, and continuous improvement of relevant evaluation policies and management mechanisms, can the overall quality of the foreign language "dual teacher" team in vocational colleges in the Yangtze River Delta region be effectively enhanced, and the healthy development of higher vocational education be promoted.

Acknowledgment

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Modern Management based on Big Data VI
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Student Engagement Models Based on Wireless Networks: Innovative Practices in Higher Education

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Abstract. This paper focuses on technology-enabled education and the enhancement of student engagement. It explores a new model of student engagement based on wireless networks. Using qualitative and quantitative research methods, with the IPTC course as a case study, the paper analyzes the application paths and effects of wireless networks in teaching. The study finds that wireless network technology breaks the limitations of time and space, lowers the participation threshold for students, and improves teaching quality. At the same time, college students are more willing to express themselves, and the forms of participation are more diverse. Moreover, the role of teachers has shifted from being 'knowledge transmitters' to 'learning guides'. The paper concludes by summarizing innovative practical experiences, noting that the 'effectiveness' and 'depth' of student participation still need to be improved. The integration of teaching design and technology remains fragmented, and the over-reliance on network tools presents challenges. It also identifies existing issues, including the need to establish a systematic teaching design guide, strengthen teacher training and platform development, and promote a 'student-centered' teaching culture, offering scalable teaching strategies for higher education.

Keywords. Student Engagement, Wireless Networks, Higher Education, Ideological and Political Theory Courses.

1. Introduction

1.1. Background

With the rapid development of information technology, higher education is undergoing an information and digital transformation aimed at improving educational quality, innovating talent cultivation methods, and promoting educational fairness and modernization. Informationization involves utilizing modern technologies to reform teaching, management, and research processes, improving the efficiency of educational resources and service quality. Digitalization, on the other hand, converts educational resources and services into digital forms, driving innovation in educational content and methods [1]. Currently, several trends characterize the digital transformation of higher education: first, online education and blended learning have become mainstream,

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gradually developing into more flexible and personalized learning; second, digital textbooks and smart classrooms facilitate personalized teaching, using big data analysis to accurately track student' learning progress; additionally, data-driven decision support and the construction of smart campuses continue to improve management efficiency and campus intelligence.

The application of VR and AR technologies in fields like medicine and engineering is also advancing immersive learning. However, the digital transformation faces challenges: outdated technological infrastructure and a lack of skilled teachers, the digital divide impacting educational fairness, and the urgent need for solutions regarding data security and privacy protection [2]. In the future, with continued technological advancements, higher education will become more intelligent and personalized, international educational resource sharing will become more accessible, and lifelong learning will become the norm. The digital transformation will profoundly reshape the structure and functions of higher education, driving social innovation and development. The widespread use of wireless networks in universities has brought profound changes, particularly in teaching, management, and campus life. Firstly, wireless networks have made teaching more flexible, allowing students to access learning materials and participate in online discussions anytime and anywhere, promoting self-directed and personalized learning. Teachers can also use mobile devices for real-time presentations and remote teaching. Secondly, wireless networks have facilitated the sharing of educational resources, enabling students to easily access digital textbooks, online courses, and virtual labs, which promotes educational equity.

With the continuous development of educational concepts, the central role of students in teaching is becoming increasingly prominent. Traditional teaching models emphasized the teacher's leading role, while modern education focuses on the student's position as the subject, with active participation and self-directed learning becoming key to improving educational quality. Students are no longer passive recipients of knowledge but active participants in knowledge exploration. Through self-learning, collaboration, and critical thinking, they can better master knowledge and develop innovative abilities and problem-solving skills.

In addition, students' feedback and opinions play an important role in improving teaching. Teachers can adjust their teaching strategies based on students' needs and feedback, making the teaching process more aligned with students' actual situations and interests. With the development of information technology, students can participate in classroom learning and teaching design at any time through online platforms and discussions, enhancing interaction and personalization in learning. Therefore, the central role of students in teaching is reflected not only in learning but also in the transformation of educational models and the improvement of teaching quality.

1.2. Problem Statement

Despite the continuous development of information technology and the increasing use of advanced teaching tools and platforms in many universities, issues such as insufficient student participation and classroom silence still persist. These problems not only affect teaching effectiveness but also limit the depth of student learning and the expansion of their thinking. Traditional classroom participation modes, such as raising hands to speak and group discussions, although promoting student engagement to some extent, have clear limitations. The hand-raising method often creates a rather one-dimensional classroom atmosphere, and the number of students who participate is limited, which often fails to fully engage all students. While group discussions can enhance interactivity, they may also be constrained by time and the number of participants.

How to innovate student participation through wireless networks has become an important issue in higher education reform? Wireless networks provide more flexible and diverse ways for students to interact, allowing them to participate in class discussions and learning activities anytime and anywhere. For example, through mobile devices, students can submit questions in real-time, participate in online polls, answer classroom questions, and even engage in virtual discussions and collaborative learning, greatly enhancing the interactivity and participation of the classroom. Additionally, wireless networks support online classes, live lectures, and educational platforms, offering a more personalized and differentiated learning experience, allowing students to choose content and learning methods based on their interests and needs [3].

The widespread use of wireless networks provides students with more opportunities to participate and offers teachers more teaching tools and strategies. Through innovative technologies, teachers can monitor students' learning status and feedback in real-time, allowing them to adjust teaching content and methods accordingly, fostering more comprehensive student participation and learning. In conclusion, fully utilizing wireless networks to innovate student participation is key to improving classroom teaching quality, enhancing active student learning, and boosting educational effectiveness.

1.3. Research Objectives

Exploring new student participation models based on wireless networks aims to break the limitations of traditional classroom interactions and stimulate active student involvement through the support of information technology. With wireless networks, students can submit questions in real time, participate in online polls, provide instant feedback, and even engage in virtual discussions and collaborative learning. This new participation model makes classroom interaction more flexible and diverse, enhancing student initiative in learning. The application path in teaching includes: teachers using wireless network platforms to publish interactive tasks, students participating in discussions and sharing viewpoints via mobile devices, and teachers monitoring students' learning progress and feedback in real-time to adjust teaching strategies.

In terms of effectiveness, this method increases classroom participation and learning interest, promotes personalized and self-directed learning. By summarizing innovative practical experiences, it can provide higher education with scalable teaching strategies, such as the use of interactive platforms, real-time feedback mechanisms, and the design of personalized learning paths, effectively supporting the improvement of education quality and the overall development of students.

1.4. Theoretical Framework and Literature Review

When exploring new student participation models based on wireless networks, relevant theories provide theoretical support. Firstly, constructivist learning theory emphasizes that learning is an active construction process, where learners actively acquire, process information, and build their knowledge systems through interaction with the environment [4]. Wireless networks, by providing abundant resources and interactive platforms, enable students to construct knowledge through self-directed learning and collaboration, thus enhancing learning outcomes.

Secondly, Interactive Learning Theory emphasizes that learning is achieved through interaction. The interaction between students, teachers, peers, and learning materials collectively facilitates the internalization of knowledge [5]. Wireless networks provide real-time interaction opportunities, allowing students to ask questions and participate in discussions at any time, enhancing classroom interactivity, and deepening and broadening learning. The Technology Acceptance Model (TAM) focuses on users' acceptance of technology, arguing that the ease of use and usefulness of a system directly affect its acceptance [6]. In a wireless network environment, the acceptance of technological platforms by both students and teachers is crucial. Only when students perceive the technological tools brought by wireless networks as easy to use and helpful can they be encouraged to participate more effectively.

Finally, Educational Technology Integration Models (such as TPACK and SAMR) provide frameworks for the effective application of educational technology [7]. The TPACK model emphasizes the integration of technology, pedagogy, and content knowledge by teachers [8], while the SAMR model guides how to enhance teaching quality through technological innovation. The widespread use of wireless networks provides the technical support for implementing these models, promoting innovation in teaching methods and improving educational quality.

Research on 'Technology to Promote Student Participation' has gained widespread attention both domestically and internationally. International studies primarily focus on how technology enhances interaction and personalized learning to promote student participation, especially in online learning and blended teaching environments. Research shows that technology can increase student engagement and facilitate collaboration and communication among students. In China, research tends to focus more on the application of wireless networks and information technology in traditional classrooms, exploring how technological tools can improve the student learning experience and enhance classroom interaction.

Typical applications of wireless networks in teaching include online quizzes, bullet screen interaction, and mobile learning platforms. Online quizzes provide real-time assessments of students' learning outcomes, increasing classroom interactivity. Bullet screen interaction, a new form of real-time feedback, allows students to comment and discuss while watching teaching videos, enhancing the sense of participation in learning [9]. Mobile learning platforms enable students to access learning resources anytime and anywhere through wireless networks, supporting personalized and self-directed learning.

However, there are still some gaps and challenges in current research. First, although the effectiveness of technology in promoting student participation has been preliminarily verified, how to optimize technology applications based on different disciplines, teaching content, and student characteristics remains an unresolved issue. Secondly, the usability of technology platforms and issues related to data privacy protection are challenges in current research. Finally, how to balance the integration of technology with traditional teaching methods, ensuring the effectiveness of technology and educational equity, requires further exploration.

2. Methods

In a wireless network environment, specific ways for student participation include bullet screens, mobile surveys, real-time voting, and collaboration platforms. Bullet screens allow students to post comments in real-time while watching instructional videos, enhancing classroom interaction and a sense of involvement. Mobile surveys and real-time voting enable immediate feedback from students, helping teachers assess learning outcomes. Collaboration platforms promote cooperative learning among students through online discussions and joint tasks, enhancing teamwork skills.

Different modes of participation have varying effects on students' cognitive, emotional, and behavioral engagement. Bullet screens and real-time voting can stimulate emotional involvement, encouraging students to express their views more actively in class. Collaboration platforms help improve cognitive engagement by promoting the exchange and collision of ideas.

When designing and guiding these modes, teachers should choose suitable interaction methods based on the course content and students' characteristics. Through well-designed tasks and feedback mechanisms, teachers can encourage participation and critical thinking. For example, in the 'Ideological and Political Theory Courses' course, interactive sessions through wireless network platforms can deepen students' understanding of the content and emotional connection to the course.

In this paper, we used teaching observation that involves directly observing the classroom teaching process to analyze student participation, learning performance, and teaching strategies, in order to assess teaching effectiveness. Then, teaching platform data analysis utilizes learning data collected from digital platforms, such as students' online activities, quiz scores, and interaction frequency, to help teachers understand students' learning progress and identify issues, allowing them to adjust teaching methods. Finally, case study involves in-depth analysis of specific courses or teaching activities to explore their implementation process, effects, and impacts, providing empirical evidence for teaching practice. For example, by observing the 'Ideological and Political Theory Courses' course and combining platform data analysis, it is possible to evaluate the specific impact of wireless network interaction modes on student participation and optimize teaching design and strategies.

3. Result and discussion

3.1. Descriptive Statistics of Self-Perception Across the Four Dimensions

In the course 'Ideological and Political Theory Courses', teaching activities will fully leverage wireless network tools to promote student participation and interaction. Specific integration methods include (1) Real-time polling and feedback. Through online platforms (such as classroom assistants or LMS), students can participate in polls, answer questions, and submit feedback during class. Teachers can quickly adjust teaching content based on poll results. (2) Bullet screen interaction. During the explanation of theoretical content, the bullet screen feature will be activated, allowing students to ask questions or engage in discussions while watching videos, enhancing classroom interaction. (3) Online surveys and quizzes. After class, online surveys or quizzes will be distributed via the wireless network to help students consolidate knowledge and assess learning outcomes. (4) Collaboration platforms. Students can access collaboration platforms via wireless networks to engage in group discussions, share learning resources, and complete assignments together.

First, we design concept. The 'flipped classroom' model be adopted, where the teacher is no longer just a knowledge transmitter, but a guide and facilitator. Course content will be provided to students through videos, reading materials, etc., and classroom time will be used for discussion, interaction, and problem-solving.

Then, we processed the teaching process. In the pre-class preparation, students will learn relevant knowledge through the learning management system (LMS) and complete online surveys or watch videos before class [10]. In the classroom interaction, teachers will use real-time polling, bullet screen interaction, etc., to stimulate student thinking and facilitate class discussions. For the group collaboration, in-class group discussions and case studies will be conducted, using wireless network platforms to share and exchange ideas. For the post-class feedback step, the online quizzes and surveys will be distributed via the platform to assess students' understanding of the course material and gather feedback on the teaching process.

Finally, we evaluation the mechanism. From the quantitative evaluation, students' learning will be assessed through online test scores, poll results, and assignment completion. From the qualitative evaluation, student participation in interactions, the quality of discussions, and classroom observations by the teacher will be used to evaluate cognitive, emotional, and behavioral engagement.

Table 1. Descriptive Statistics of Self-Perception Across the Four Dimensions.

Items	N	Minimum Value	Maximum Value	Mean	Standard Deviation
Self-Perception Evaluation of Cognitive Engagement	3992	5.00	10.00	6.48	1.267
Self-Perception Evaluation of Emotional Engagement	3992	4.00	10.00	6.91	1.553
Self-Perception Evaluation of Intentional Engagement	3992	4.00	10.00	6.19	1.462
Self-Perception Evaluation of Behavioral Engagement	3992	5.00	10.00	6.35	1.578
Valid Cases	3992				

We can see, from the Table 1, the mean scores for college students' self-perception evaluations of cognitive engagement, emotional engagement, intentional engagement, and behavioral engagement in ideological and political courses are 6.48, 6.91, 6.19, and 6.35, respectively. All scores are above 6, indicating that students have a relatively high level of self-evaluation across all dimensions. This suggests that college students in China currently demonstrate sufficient investment and good performance in ideological and political courses.

3.2. Practical Process and Observation

Through bullet screens, real-time polling, and other methods, students were able to actively participate in discussions and provide feedback. They could immediately ask questions and receive answers from the teacher. Most students showed high enthusiasm for participation, especially in the bullet screen interaction and real-time polling sessions. In group discussions, students engaged deeply with the content and actively exchanged ideas. Teachers adjusted the pace and content of the lesson based on real-time polling and feedback, ensuring that teaching activities aligned with students' needs. They also monitored students' progress via the online platform and provided targeted teaching interventions.

3.3. Analysis of Practical Outcomes

We analysis the course practical outcomes as follows:

Table 2. Predictive Analysis Table of Self-Perception Evaluation on Student Engagement.

		UC		SC			Collinearity Statistics			
	Model	B	Standard Error	Beta	t	Significance	Eigenvalue	VIF	R^2	F
1	Constant	274.12	3.21		85.34	0.13	4.89		0.22	286.03
	CES	0.94	0.15	0.09	6.46	0.00	0.05	1.00		
	EES	1.00	0.12	0.12	8.36	0.00	0.05	1.00		
	IES	0.87	0.13	0.10	6.87	0.00	0.00	1.00		
	BES	14.04	0.45	0.44	31.52	0.00	0.02	1.00		

Note: UC=Unstandardized Coefficients, SC=Standardized Coefficients, CES=Cognitive Engagement Self-Assessment, EES=Emotional Engagement Self-Assessment, IES=Intentional Engagement Self-Assessment, BES=Behavioral Engagement Self-Assessment

From the Table 2, we could see R^2=0.22，F=286.03，P=0.000, which means the four dimensions have a positive predictive effect on student engagement in ideological and political courses for college students.

Firstly, the self-perception evaluation of cognitive engagement has the greatest influence weight (eigenvalue=0.05), indicating that college students now have a sufficient understanding of ideological and political courses. Students place a high value on studying ideological and political theory courses, and mastering these courses is the first step in enhancing cognitive engagement.

Secondly, the self-perception evaluation of emotional engagement also has a significant influence weight (eigenvalue=0.05), showing that college students believe they like ideological and political courses to some extent, are willing to study them, and have invested a considerable amount of emotion and interest in these courses. Thirdly, the self-perception evaluation of intentional engagement has the smallest influence weight (eigenvalue=0.00), suggesting that college students believe that intentional engagement does not affect their engagement in ideological and political courses, and that the other three dimensions are the key factors affecting student engagement.

Finally, the self-perception evaluation of behavioral engagement has a relatively small influence weight (eigenvalue=0.02), indicating that college students have relatively weak motivation in terms of action towards studying ideological and political courses and insufficient proactive behavioral engagement. Therefore, in the process of teaching ideological and political courses, it is crucial to focus on practice. While enhancing students’ full understanding of ideological theory, efforts should be made to encourage them to apply the theories they learn to practice, achieving the transformation from ‘knowing’ to ‘doing’.

3.4. Changes in Student Participation

First, data from online polling and quizzes showed a 30% increase in participation frequency and a significant improvement in correct answer rates compared to traditional classrooms. Second, students' mastery of knowledge also showed notable improvement. Classroom discussions were more active, and students presented deeper insights, especially in bullet screen interactions, demonstrating higher emotional engagement and intellectual exchange. Finally, teachers expressed high satisfaction with the teaching results, noting that wireless network tools allowed for real-time understanding of students' learning progress and helped effectively adjust teaching strategies. Teachers also observed a significant increase in student interest and participation in the classroom.

3.5. Problems and Optimization Suggestions

Some students initially struggled with using the technological platforms, leading to some barriers in participation. Additionally, network issues affected student engagement, impacting the overall learning experience. More technical training should be provided to help students become familiar with the online platforms. Also, optimizing the network environment to ensure stable connectivity will improve participation. Furthermore, teachers can design a wider variety of interactive tasks to further enhance student engagement and learning outcomes. Through this practical case, we can observe the positive impact of wireless network tools on student participation. However, there is a need to optimize the technological applications and classroom management to achieve better teaching outcomes.

4. Conclusion

4.1. Research Findings

Studies have shown that the use of wireless networks helps break the limitations of time and space, lowers the participation threshold, and improves the quality of engagement. With wireless networks, students can participate in classroom interactions anytime and anywhere, making it easier for them to speak up and engage in discussions, and providing more diverse forms of participation, significantly increasing student enthusiasm. Meanwhile, the teacher' s role shifts from the traditional 'knowledge transmitter' to a 'learning guide,' focusing more on guiding students to think and participate, creating a more interactive and dynamic learning environment.

4.2. Issues and Reflection

Although student participation has increased, the ‘effectiveness’ and ‘depth’ of their involvement remain challenges. Some students’ participation is superficial, lacking deep reflection and critical thinking. In addition, there is still a disconnection between teaching design and the integration of technology, as the use of technological tools sometimes does not align effectively with teaching goals. Over-reliance on network tools also introduces new challenges, such as technical failures and unfamiliarity with platform operations, which may affect teaching outcomes and student engagement.

4.3. Suggestions for Promotion

To better promote the use of wireless network tools in teaching, it is recommended to establish a systematic teaching design guide to help teachers design interactive activities and fully utilize technological tools to enhance teaching effectiveness. Moreover, teacher training and platform development should be further strengthened to ensure that teachers can effectively use these tools. Additionally, promoting a ‘student-centered’ teaching culture is essential [10], emphasizing students’ active participation and responsibility in the learning process to achieve more efficient and comprehensive educational outcomes.

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