Comprehensive Measurement of Space Efficiency of Chinese Pharmaceutical Cold-chain Logistics in the Post-pandemic Era Based on Envelope Analysis

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ABSTRACT With the evolution of the COVID-19 pandemic, the combined influence of the Two-Vote System, the New Medical Reform, and the rapid proliferation of the "Internet + Healthcare" model has brought Chinese pharmaceutical cold-chain logistics into a stage of policy-intensive growth. Market scale has continued to expand, and service quality has improved, while regional spatial allocation efficiency remains uneven. Through envelope analysis integrated with spatial comparative analysis, this study measures the geospatial allocation efficiency of Chinese pharmaceutical cold-chain logistics across 31 provinces, defining space efficiency as the capacity of geographic units to optimize logistics outputs relative to localized infrastructure and resource constraints. Panel data from 2019 to 2022 are analyzed using DEAP VERSION 2.1 to evaluate dynamic efficiency through the Malmquist index and static efficiency through CCR and BCC models. Results show that the overall efficiency level is high but still below the DEA frontier, with significant regional disparities and total factor productivity strongly dependent on technological progress. The findings support policy guidance, infrastructure investment, talent development, and RFID/wireless temperature-monitoring systems for coordinated high-quality development.

INDEX TERMS envelope analysis, pharmaceutical cold chain, space efficiency, RFID sensing, cold-chain logistics

I. INTRODUCTION

With the quick development of the global pharmaceutical industry, the primary pharmaceutical cold-chain logistics industry, represented by vaccines, blood products, and in vitro testing reagents, has experienced robust expansion[1]. Especially the outbreak of the COVID-19 pandemic has profoundly altered the market landscape of China's pharmaceutical cold chain logistics, propelling the high-quality development of the pharmaceutical cold chain logistics supply chain[2]. Meanwhile, the implementation of new policies like "Internet + pharmaceuticals," "volume-based procurement," and "two-vote system" have also driven the significant scaling of China's pharmaceutical cold-chain market capacity[3]. It is measured that up to December 2023, the sales volume of the Chinese pharmaceutical cold-chain logistics industry is nearly 608.45 billion yuan, and the logistics cost is about 27.58 billion yuan. As a high-end scenario in the logistics industry system, pharmaceutical cold-chain logistics has far higher profitability than general logistics and higher technical requirements in links such as warehousing and transportation [4]. Driven by the policies and the trillion market scale, the Chinese pharmaceutical cold-chain market competition has become increasingly intense[5]. Particularly after the Chinese government enacted new pharmaceutical cold-chain regulations in 2020, the degree of specialization in pharmaceutical cold-chain logistics has increased rapidly and achieved unprecedented development under the influence of the COVID-19 pandemic[6] (see Figure 1).

Nevertheless, it is also essential to clearly understand that as the unprecedented logistics demands of the pandemic peaked between 2020 and 2022, the development of the Chinese pharmaceutical cold-chain logistics industry was characterized by heavy policy-driven distribution, particularly for vaccines and emergency medical supplies[7]. In this study, the panel data of 31 provinces and cities in China over the 2019–2022 period was taken as the study object, and a complete input index system was established from three dimensions: capital, human resources, and technology[8]. Apart from that, two dimensions of production capacity and industrial added value were incorporated to measure the efficiency of pharmaceutical cold-chain logistics in different Chinese provinces, cities, and the whole nation[9]. The data was derived from the official website of the Chinese government, industry survey reports, etc., with relatively good reliability. CCR and BCC models were adopted to comprehensively analyze the space efficiency difference of Chinese pharmaceutical cold-chain logistics[10].

Furthermore, the space efficiency of pharmaceutical cold-chain logistics was dynamically analyzed through the Malmquist index[11]. Combined with the results of model analysis and related theories, the returns to scale of 31 provinces and cities were focused on providing some very targeted and viable optimization suggestions[12]. Additionally, Chinese experiences in developing pharmaceutical cold-chain logistics after the COVID-19 pandemic were introduced[13], which provided references for producing the pharmaceutical cold-chain logistics industry in various countries.

II. MARKET CONCENTRATION-DRIVEN PROSPECT ANALYSIS

Based on the current landscape, China's pharmaceutical cold chain logistics sector exhibits high concentration among leading enterprises. In terms of market share for 2024, Sinopharm Group, China Resources Pharmaceutical Group, and Shanghai Pharma emerged as the industry's top three players, commanding market shares of 26%, 15%, and 11% respectively ($\mathrm{CR}_3 = 52\%$). Additionally, third-party logistics specialists represented by SF Pharmaceuticals and JD Logistics held approximately 28% market share. According to the formula:

$$\mathrm{HHI} = \sum (S_i)^2 \tag{1}$$

Based on calculations, the HHI (Herfindahl-Hirschman Index) for the top three enterprises is $26^2 + 15^2 + 11^2 = 3402$, indicating a highly concentrated market. The 2024 Pharmaceutical Supply Chain Standards will accelerate mergers among small and medium enterprises, with CR10 (concentration ratio of the top 10 players) projected to rise from 58% in 2023 to 67% by 2025. Additionally, Figure 1 illustrates the time-series evolution of China's pharmaceutical cold chain logistics costs and segmented market conditions.

From a market concentration perspective, China's pharmaceutical cold chain sector is experiencing rapid development, with concentration levels continuously increasing. Leading enterprises are expanding their scale and gaining market share year-over-year, driven by rising cold chain logistics costs and policy guidance. This demonstrates that Chinese pharmaceutical cold chain companies possess sufficient capital strength to propel industry advancement, particularly in digital transformation.

Building upon this developmental momentum in China's cold chain logistics market, this study analyzes the spatial efficiency of pharmaceutical cold chain logistics specifically during the peak pandemic period (2019–2022), accounting for the significant impact of government-led emergency logistics interventions. It aims to identify regional disparities in cold chain logistics development across China and uncover latent commercial opportunities.

III. SELECTION OF MODEL AND STUDY METHOD

Through envelope analysis, this study investigated the efficiency of pharmaceutical cold-chain logistics in 31 Chinese provinces and cities. For the analysis of static efficiency, the CCR model and BCC model were used[14]. For the analysis of dynamic efficiency, the Malmquist index approach was adopted to measure the efficiency changes[12].

A. CCR MODEL

The CCR model is a standard envelope analysis model and a crucial tool for measuring the overall efficiency of the decision-making unit. The CCR model assumes a fixed input-output ratio (returns to scale) and calculates the efficiency frontier using linear programming and a duality model[14]. Namely, the comprehensive efficiency is calculated via CRS. Hence, when the input-output ratio of the decision-making unit reaches the maximum, it means the highest efficiency.

Thus, the input-output efficiency of the Kth decision-making unit is represented as:

$$\max \frac{\sum_{j=1}^{n} U_j Y_{jk}}{\sum_{i=1}^{m} V_i X_{ik}} \tag{2}$$

Formula (2) V_i represents the weight of the input index; U_j it represents the weight of the output index. The specific input and output indexes are expressed by X_k and X_k. Furthermore, the ith input or the jth output index is expressed as X_{ik} and Y_{jk}. The formula represents the particular quantity of these two indexes by m and n.

To ensure the model's validity, it is essential to meet the following limiting conditions:

$$\begin{aligned} &\frac{\sum_{j=1}^{n} U_j Y_{jk}}{\sum_{i=1}^{m} V_i X_{ik}} \leq 1, \\ &U_j \geq 0,\ V_i \geq 0\ (i - 1, 2, \ldots, m;\ j = 1, 2, \ldots, n). \end{aligned} \tag{3}$$

B. BCC MODEL

The BCC model is a non-parametric technical efficiency analysis model and an envelope analysis model proposed by Banker et al. based on the assumption of non-fixed returns to scale. It is mainly applied in the multi-input, multi-output static analysis[15]. No concrete form of production function is required, effectively eliminating the influence of subjective factors[16]. Variable Returns to Scale mode (VRS) is used. In the VRS model, pure technical and scale efficiency

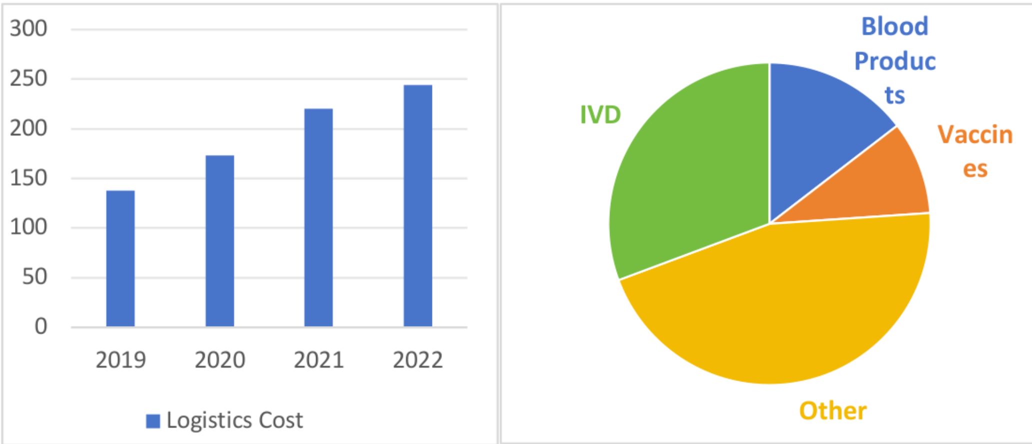

FIGURE 1. Chinese pharmaceutical cold-chain logistics expenses and market segments over the 2019–2022 periods. Data source: CFLP Cold Chain Committee sorted out by this paper

are adopted to embody the comprehensive technical efficiency to more clearly reflect the comprehensive efficiency change caused by scale efficiency changes[15]. If there are N decision-making units, the input-output efficiency of the Kth decision-making unit is expressed as:

$$\frac{\sum_{j=1}^{n} U_j Y_{jk} - u0}{\sum_{i=1}^{m} V_i X_{ik}} \tag{4}$$

Formula (4) U_j represents the weight of the input index and V_i the weight of the output index. The specific input and output indexes are expressed by X_k and Y_k. The particular quantity of the two indexes is expressed by m and n in the formula. $u0$ Represents an accessible value[15]. Likewise, it is essential to meet the following limiting conditions:

$$\text{s.t.} \quad \frac{\sum_{j=1}^{n} U_j Y_{jk} - u0}{\sum_{i=1}^{m} V_i X_{ik}} \leq 1, \quad U_j \geq 0,\ V_i \geq 0\ (i - 1, 2, \ldots, m;\ j = 1, 2, \ldots, n). \tag{5}$$

In formula (5), when returns to scale increase, it is expressed as $u0 < 0$; Otherwise, $u0 > 0$. $u0 = 0$ indicates fixed returns to scale[1].

C. MALMQUIST INDEX MODEL

Regardless of the CCR model mentioned above or the BBC model, the results reflect the static comparison results of efficiency, which show the change in decision-making unit efficiency over time. Namely, it is limited to static evaluation[1]. Given incomparability, the efficiency values of different years are not directly compared. In response to this issue, Swedish economist Malmquist proposed the Malmquist index in 1953. Grounded on the productivity frontier theory[1], it effectively reflects the efficiency change over time and thus presents the change tendency and degree of efficiency.

Assuming that the input variable of the decision-making unit is X and the output variable is Y in the two time periods of t-1 and t, then the changes of efficiency values in the two time periods of t-1 and t are expressed using the total factor productivity index (TFP), namely:

$$\text{TFP} = \frac{Y_t / X_t}{Y_{t-1} / X_{t-1}} \tag{6}$$

Formula (6) Y_t, X_t represents the output and input of phase t. The output and input of phase t-1 are Y_{t-1} as X_{t-1} follows[14]:

Indeed, t-1 is the reference value, which is compared with the t period to understand the changes in TFP. If TFP > 1 means rising productivity; Otherwise, it means decreasing productivity.

Moreover, effect represents technical efficiency; tech represents technical progress; pech represents pure technical efficiency; such represents scale efficiency; teach represents total factor productivity. Thus, the following formula is obtained[18]:

$$\text{tfpch} = \text{effch} \times \text{techch} \tag{7}$$

$$\text{techch} = \text{pech} \times \text{sech} \tag{8}$$

All in all, pure technical efficiency, technical efficiency, and scale efficiency jointly determine TFP[19]. Following formulas (7) and (8), if the value of the three is greater than 1, it is favorable to the increase of TFP; otherwise, it will trigger the decline of the specific value of TFP.

IV. EVALUATION INDEX SELECTION AND DATA SOURCES

A. SELECTION OF EVALUATION INDEX

In the index selection process, it is essential to follow the principles of scientificity, comprehensiveness, operability, significance, and data accessibility and fully consider the characteristics of the pharmaceutical cold-chain logistics industry[20]. Combined with the previous study results and the features of the DEA model, four input indexes reflecting spatial and resource commitment and three output indexes focusing on physical and economic throughput are chosen (see details in Table 1). To better align with the definition of "space efficiency," the input indicators prioritize infrastructure density, while the output indicators emphasize the physical utilization of logistics space (see details in Table 1)[12].

TABLE 1. Efficiency index of Chinese pharmaceutical cold-chain logistics

First level index	Second level index	Variable name	Unit
Input index	Number of employees in the logistics industry	X1	Ten thousand people
	Fixed investment	X2	One hundred million yuan
	Standard cold storage area per unit of land	X3	Square meters/hectare
	Conformity to GSP standard cold storage capacity	X4	Ten thousand tons
Output index	Physical volume of cold-chain throughput	Y1	Ten thousand tons
	Gross traffic of cold-chain logistics	Y2	One hundred million tons
	Spatial turnover volume (Physical-weighted)	Y3	One hundred million ton-km

B. DATA SOURCES OF EVALUATION INDEX

Because it started relatively late, Chinese pharmaceutical cold-chain logistics development remains early, and it is challenging to acquire related data. Meanwhile, there is no complete independent statistical accounting system. Thus, the data in this study is primarily collected from the official website of the CFLP Cold Chain Committee, and multiple industry survey reports have been synthesized. Some data come from the China Statistical Yearbook, the Statistical Yearbook of Chinese Provinces, the Chinese Cold-chain Logistics Development Report, and the China Federation of Logistics and Purchasing Report[21].

V. EMPIRICAL ANALYSIS OF SPATIAL EFFICIENCY OF PHARMACEUTICAL COLD CHAIN LOGISTICS

A. VARIABLE ISOTROPIC TEST

In the practical use of the DEA model, an input increase is required to cause a corresponding increase in output. Hence, an isotropic test should be conducted on the input and output indexes. In this study, Pearson correlation coefficients were analyzed using SPSS21 variable correlation. Then, the statistical results were obtained (see Table 2)[22].

TABLE 2. Isotropic test of efficiency evaluation index of pharmaceutical cold-chain logistics

Variable	The gross amount of cold-chain logistics	Gross traffic of cold-chain logistics	Turnover volume of cold-chain logistics
Number of employees in the logistics industry	0.848**	0.904**	0.689**
Fixed investment	0.842**	0.818**	0.760**
Total transport mileage	0.941**	0.855**	0.689**
Conformity to GSP standard cold storage capacity	0.578**	0.667**	0.378*

Note: ** is a significant correlation at the level of 0.01; * is a significant correlation at the level of 0.05.

The statistical data in Table 2 reveals that all input and output variables are significantly correlated at 0.01. "conformity to GSP standard cold storage capacity" and "turnover volume of cold-chain logistics" are correlated considerably at 0.05. The result shows that the input and output indexes pass the isotropic test, and the DEA model is used for analysis[23].

B. COMPREHENSIVE EFFICIENCY ANALYSIS

The panel data of 31 Chinese provinces and cities over the 2019–2022 periods were incorporated into the CCR model of DEAP VERSION 2.1 software. Additionally, the comprehensive efficiency of pharmaceutical cold-chain logistics in various Chinese regions was systematically analyzed to evaluate the spatial allocation of pharmaceutical cold-chain resources across various administrative regions. The specific calculation results are presented in Table 3.

In the DEA model, the higher the efficiency of resource allocation, the closer the value is to 1, and the higher the input-output ratio of resources. Conversely, it means that the lower the efficiency of resource allocation, the lower the input-output ratio of resources. Based on the analysis of the calculation results in Table 3 and the general classification standards in this field, this study considers that the comprehensive efficiency from 0.5 to 0.8 is medium. At the same time, less than 0.5 is poor, and above 0.8 is excellent[24].

Within the four years from 2019 to 2022, the comprehensive efficiency of Chinese pharmaceutical cold-chain logistics presents inevitable volatility (see Figure 2)[24].

The information in Figure 2 demonstrates that after 2019, the comprehensive efficiency of Chinese pharmaceutical cold-chain logistics started to rise quickly, from the lowest value of 0.841 in 2019 to 0.887 in 2020, and further increased to 0.888 the following year. This situation is directly associated with the emergency logistics surge required for national pandemic control (e.g., mass vaccine distribution) and the interventionist policy guidance of the Chinese government, which artificially inflated efficiency markers in specific regions during 2020–2022[25,26].

As shown by the figure, among six Chinese administrative regions, except for a slight drop in the comprehensive effi-

TABLE 3. Comprehensive efficiency of pharmaceutical cold-chain logistics in 31 Chinese provinces and cities

Administrative region	Province and city	2022	2021	2020	2019	Provincial and municipal average	Regional comprehensive efficiency
North China	Beijing	0.388	0.459	0.528	0.576	0.409	0.843
	Tianjin	0.831	0.894	1.000	0.866	0.780	
	Hebei	1.000	1.000	1.000	1.000	1.000	
	Shanxi	1.000	1.000	1.000	1.000	1.000	
	Inner Mongolia	0.995	0.944	1.000	1.000	0.985	
	Average	0.854	0.871	0.926	0.906		
Northeast China	Liaoning	1.000	1.000	1.000	1.000	1.000	0.802
	Jilin	0.653	0.909	0.810	0.870	0.783	
	Heilongjiang	0.500	0.454	0.623	1.000	0.609	
	Average	0.727	0.797	0.821	0.976		
East China	Shanghai	1.000	1.010	1.000	1.000	0.968	0.874
	Jiangsu	0.553	0.773	0.656	0.689	0.649	
	Zhejiang	0.952	0.829	0.839	0.798	0.851	
	Anhui	1.000	1.000	1.000	1.000	1.000	
	Fujian	0.799	0.651	0.671	0.796	0.789	
	Jiangxi	1.000	1.000	1.000	1.000	0.962	
	Shandong	0.939	1.000	0.793	0.994	0.836	
	Average	0.904	0.907	0.864	0.909		
South Central China	Henan	0.962	1.000	0.803	0.920	0.881	0.905
	Hubei	0.934	0.834	0.752	1.001	0.886	
	Hunan	0.754	0.655	0.809	0.833	0.757	
	Guangdong	0.807	0.765	1.000	0.970	0.825	
	Guangxi	1.000	1.000	1.000	1.000	1.000	
	Hainan	1.000	1.000	1.000	1.000	1.000	
	Average	0.919	0.889	0.908	0.963		
Southwest China	Chongqing	0.931	1.000	1.000	0.890	0.957	0.946
	Sichuan	0.837	0.727	0.663	0.775	0.806	
	Guizhou	0.892	0.890	0.897	1.000	0.931	
	Yunnan	1.000	1.000	0.993	1.000	0.998	
	Xizang	1.000	1.000	1.000	1.000	1.000	
	Average	0.943	0.941	0.922	0.950		
Northwest China	Shaanxi	1.000	1.000	0.895	1.000	0.994	0.884
	Gansu	0.924	0.982	0.931	0.936	0.942	
	Qinghai	0.424	0.343	0.591	0.919	0.537	
	Ningxia	1.000	1.000	0.881	0.897	0.973	
	Xinjiang	0.987	1.000	1.000	1.000	0.991	
	Average	0.878	0.881	0.865	0.861		
National Average		0.885	0.888	0.887	0.841		0.884

ciency of pharmaceutical cold-chain logistics in North China after 2020[27] and a persistent decline in the thorough efficiency of pharmaceutical cold-chain logistics in Northeast China, the comprehensive efficiency trend of pharmaceutical cold-chain logistics in the remaining four administrative regions is the same as that of the whole nation This situation is explained in two ways. On the one hand, considering the cold-chain logistics infrastructure in Northeast China is old. Remarkably, there is a deficient new GSP standard cold storage. On the other hand, the COVID-19 pandemic in North China is rapidly controlled[27], biomedicine is advanced, and there is no significant demand for local cold-chain transportation[28].

Regarding regional comprehensive efficiency, the thorough efficiency of pharmaceutical cold-chain logistics in Southwest China is the highest and ranks first while the comprehensive efficiency of Northeast China ranks last. Moreover, there are seven provinces with an average comprehensive efficiency of 1, and the level of resource allocation is outstanding[29]. Over that, ten provinces have an average comprehensive efficiency of 0.9–1.0. Overall, the efficiency of pharmaceutical cold-chain logistics resources allocation in Northeast China and North China still has a large room for improvement Apart from that, the pharmaceutical cold-chain logistics in Southwest China has suddenly risen and developed swiftly. This is attributed to the Chinese government's implementation of a strategy for large-scale development of West China around 2000. The rapid growth of local land routes and waterway transportation contributes to the efficiency and overall improvement of pharmaceutical cold-chain logistics in this region[29].

C. PURE TECHNICAL EFFICIENCY ANALYSIS

The panel data of 31 Chinese provinces and cities over the 2019–2022 periods were incorporated into the DEAP VERSION 2.1 software BCC model to calculate the pure technical efficiency of product cold-chain logistics (see specific calculation results in Table 4).

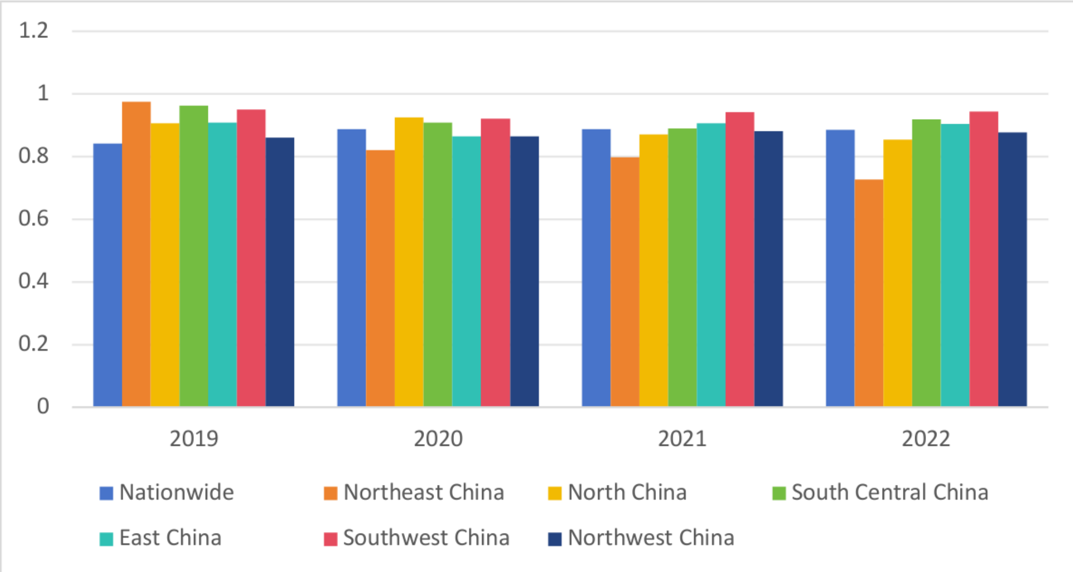

FIGURE 2. Changes in the comprehensive efficiency of Chinese pharmaceutical cold-chain materials over the 2019–2022 periods

TABLE 4. Pure technical efficiency of pharmaceutical cold-chain logistics in 31 Chinese provinces and cities

Administrative region	2022	2021	2020	2019	Regional pure technical efficiency
North China	0.913	0.923	0.929	0.954	0.919
Northeast China	0.757	0.845	0.856	0.977	0.833
East China	0.961	0.915	0.949	0.936	0.949
South Central China	0.983	0.950	0.962	1.000	0.978
Southwest China	0.994	0.947	0.949	0.999	0.979
Northwest China	1.005	1.000	1.009	1.000	1.000
National Average	0.950	0.940	0.949	0.981	

According to the calculation results in Table 4, the average pure technical efficiency of Chinese pharmaceutical cold-chain logistics over 2019–2022 always remains around 0.95, fully validating that the resources' return on investment is high. Only Northeast China has relatively low pure technical efficiency. This is mainly associated with the low technical level, inadequate management, and deficient talent reserve, hindering the high-quality development of this region's pharmaceutical cold-chain logistics industry. Following the cold-chain logistics development planning of the "14th Five-year Plan", it is essential to guide the allocation of funds, talents, technology, and other elements towards more weak links in the cold chain logistics via market-driven and government-guided modes, focus on improving weaknesses, and consolidate the foundation for the industry development. Compared with the cold-chain logistics industry of pharmaceuticals and food, the pharmaceutical industry is unique and poses higher requirements for relevant equipment and settings[30]. At the same time, related local policies are continuously introduced to boost the fast development of Chinese pharmaceutical cold-chain logistics. Hence, in subsequent development, it is essential to increase capital and talent investment in pharmaceutical cold-chain logistics technology innovation and conduct more practical and effective endeavors to improve technical efficiency. Specifically, it is necessary to develop towards informatization actively, holistically introduce emerging technologies like cloud computing, big data, and blockchain[31], and facilitate the innovative development of pharmaceutical cold-chain logistics from the policy and taxation[32].

D. SCALE EFFICIENCY ANALYSIS

Similarly, scale efficiency is a vital component of the total factor productivity index, primarily influenced by the enterprise scale[33]. If the scale efficiency is 1, it suggests that the production scale reaches the optimal level. If the scale efficiency is less than 1, it indicates that the production scale and production efficiency are not adaptable and the scale is invalid. The calculation results of scale efficiency of pharmaceutical cold-chain logistics in 31 Chinese provinces and cities are presented in Table 5.

TABLE 5. Pure scale efficiency of pharmaceutical cold-chain logistics in 31 Chinese provinces and cities

Administrative region	2022	2021	2020	2019	Regional scale efficiency
North China	0.950	0.955	0.997	0.971	0.921
Northeast China	0.984	0.970	0.978	0.999	0.993
East China	0.960	1.000	0.938	0.995	0.948
South Central China	0.964	0.962	0.972	0.986	0.949
Southwest China	0.977	0.998	0.994	0.976	0.992
Northwest China	0.902	0.882	0.884	0.961	0.906
National Average	0.955	0.971	0.962	0.984	

According to the statistical data in Table 5, the overall scale efficiency and scale effect of Chinese pharmaceutical cold-chain logistics are relatively high, verifying that the overall planning of Chinese pharmaceutical cold-chain logistics is rational and provides the development of the domestic pharmaceutical cold-chain industry with support. Regarding region, only the scale efficiency of Northwest China approaches 0.9, implying that there is an inadaptable situation between the production scale and production efficiency in this area, and resources are improperly allocated[34]. Thus, for regions like Northwest China where scale efficiency is the primary bottleneck, policy focus should shift from physical asset expansion to the strategic consolidation of existing resources and the elimination of redundant capacity to achieve optimal scale returns.

Other regions have generally high regional scale efficiency. The change tendency of the returns to scale should be further combined to judge whether adjusting the scale of the pharmaceutical cold-chain logistics industry is essential to avoid blind input of resources.

E. DYNAMIC ANALYSIS OF THE MALMQUIST INDEX

This part adopted the Malmquist index for dynamic analysis to analyze further and discuss the time change of pharmaceutical cold-chain logistics industry efficiency in 31 Chinese provinces and cities over the 2019–2022 periods (see the statistical results in Table 6).

TABLE 6. Malmquist index of pharmaceutical cold-chain logistics efficiency in 31 Chinese provinces and cities cited

Year	2019–2020	2020–2021	2021–2022	Mean value
Technical efficiency change index	1.025	1.015	0.961	1.0004
Technical progress change index	0.845	1.046	0.996	0.9624
Pure technical efficiency change index	1.038	1.014	0.988	1.0135
Scale efficiency change index	1.015	1.029	0.999	1.0145
Total factor productivity index	0.842	1.031	0.932	0.935

As showin Table 6, the technical progress change index is always higher than the technical efficiency change index, except from 2019 to 2020. That is to say, the technical progress has a more pronounced contribution to the total factor productivity. The sustained development and improvement of technologies in multiple fields, such as cold chain storage and refrigerated vans, is now a crucial factor driving the Chinese total factor productivity growth[35]. The technical efficiency change index is always greater than one until 2021, yet there is a sudden drop in the 2021–2022. This is likely associated with mismanagement and poor market application. Notably, the lower efficiency observed in some developed eastern provinces compared to central regions may stem from "resource redundancy." In these areas, massive capital injection into high-end infrastructure has reached a stage of diminishing marginal utility, where the spatial growth rate of infrastructure exceeds the actual growth rate of pharmaceutical circulation volume, leading to temporary idle capacity[36]. The rapid growth of the pharmaceutical cold-chain logistics market scale has promoted continuous expansion of the gap of high-end technical talents. In the follow-up development, it is essential to fortify the training of practitioners, implement multifaceted strategies, such as university-industry collaborative education programs, effectively improve the talent reserve level of the pharmaceutical cold-chain logistics industry, and strengthen the technology application capacity. After 2020, the scale efficiency change index has always been more significant than the pure technical progress change index, demonstrating that the pure technical efficiency factor is the primary reason for relatively low technical efficiency. Hence, the follow-up work should focus on the study of technology, development, and innovation[37]. Before 2020, the pure technical progress change index was more significant than the scale efficiency change index, revealing that the low technical efficiency problem in the Chinese pharmaceutical cold-chain logistics system caused by unreasonable scale input has been fundamentally solved after 2020, and the industrial construction scale is relatively ideal.

VI. CONCLUSIONS

Firstly, the efficiency of Chinese pharmaceutical cold-chain logistics is relatively high, but with significant fluctuation due to the influence of multiple factors. Moreover, the comprehensive efficiency of Northeast China and North China is slightly lower than the national average level, which is the core region for constructing pharmaceutical cold-chain logistics systems in the future. For international investors, this represents a significant market opportunity characterized by promising investment prospects and easier access to a series of policy incentives from the Chinese government.

Secondly, scale and technical efficiency influence the comprehensive efficiency of Chinese pharmaceutical cold-chain logistics and exhibit notable regional differences. Thus, it is essential to flexibly formulate policies based on the comparison efficiency and technical efficiency in specific provinces and cities. For the Chinese government, this serves as a crucial driver for advancing the entire pharmaceutical cold chain logistics industry, while simultaneously providing a vital practical basis for achieving high-quality development in the pharmaceutical cold chain logistics market. Consequently, policy formulation should demonstrate greater regional differentiation—offering more tailored and actionable guidance to support the growth of pharmaceutical cold chain logistics industries across diverse regions.

Thirdly, technical progress is the primary factor driving the total factor productivity growth, while the level of total factor productivity is subject to the technical efficiency change index. From this perspective, technological advancement remains fundamental to securing further progress in the pharmaceutical cold chain logistics industry. Particularly as the industry transitions out of the pandemic-control phase, only through continuous innovative breakthroughs to replace temporary policy-driven growth can technical efficiency be elevated, thereby driving holistic advancement across the sector. This trajectory has been validated globally, as evidenced by Germany's AI-powered warehouse automation (reducing errors by 37%) and Singapore's blockchain-enabled vaccine traceability systems. Thus, governments worldwide should intensify their focus on and investment in these critical innovations.

Lastly, in combination with the study results, this paper sums up that the Chinese government should implement differentiated strategies: regions with low pure technical efficiency must prioritize digital management and talent introduction, while regions with low scale efficiency should avoid over-investment in infrastructure and instead focus on cross-regional resource sharing and operational streamlining. Apart from that, essential measures should be adopted to break the obstacles in the pharmaceutical cold-chain logistics market between different places and comprehensively popularize the experiences of well-developed regions in resource allocation, management, etc. Besides, the cross-regional pharmaceutical cold-chain logistics information platform should be actively explored to decrease operation costs. Great emphasis should be placed on the training and introduction of high-end compound talents in the pharmaceutical cold-chain logistics industry. Apart from active innovation of management methods and introduction of advanced management tools, it is crucial to conduct technical application capacity construction to accelerate the marketization transformation of scientific and technological achievements.

AUTHOR CONTRIBUTIONS

Conceptualization – Xiuying Wang and Bingjie Sun; methodology – Xiuying Wang and Bingjie Sun; investigation – Xiuying Wang and Bingjie Sun; writing-original draft preparation – Xiuying Wang and Bingjie Sun. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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