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Research Design on the Efficiency of Hubei Provincial Government's Healthcare Expenditure Based on Applied Mathematical Concepts

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Abstract: Mathematics, continuously uncovers deeper laws in nature and society, expanding the boundaries of human knowledge. Particularly in the social sciences, the application of mathematics exhibits unique appeal and has a profound impact on fields such as economics and public administration. This study examines the efficiency of healthcare expenditure by the Hubei provincial government, based on applied mathematical concepts and utilizing the Data Envelopment Analysis method combined with the Malmquist index model. The empirical analysis aims to explore the effectiveness of government healthcare investments and to provide a scientific basis for improving public financial efficiency. Additionally, this research will aid the author in enhancing core competencies in mathematical reasoning, modeling, data processing, and analysis, laying a solid foundation for future studies in applied mathematics and public policy. This study offers valuable insights into the efficiency of healthcare spending in Hubei Province and serves as a reference for the allocation efficiency of public resources by governments in other regions.

Keywords: Applied mathematical concepts, Malmquist index, Government healthcare expenditure efficiency

1. Introduction

Mathematics, being inherently abstract and lacking concrete physical objects, finds application across various fields, including physics, engineering, and computer science, establishing itself as a highly versatile discipline [1]. In the 21st century, employing mathematical formulas, symbols, graphics, and algorithms to characterize and interpret real-world problems has been widely recognized as an optimal approach for solving practical issues [2]. As an essential repository of high-tech knowledge, mathematics—and specifically applied mathematical thought and practice—has emerged as a focal area of research in the mathematical sciences. Many countries have long emphasized the importance of applied mathematics education. For instance, national high school curricula and textbooks in countries like UK, USA, Germany, Denmark, and the Netherlands underscore its critical role. In 1975, the U.S. CBMS recommended the inclusion of mathematical modeling in high school curricula, later organizing the first nationwide Mathematical Contest in Modeling for college students in 1985 [3]. In 2012, Germany introduced a high school mathematics education standard that emphasized cultivating mathematical modeling, problem-solving, and application skills [4]. In China, numerous

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universities have similarly promoted applied mathematics through competitions, fostering applied mathematical thinking and practice. Building on this foundation, this study applies Data Envelopment Analysis (DEA) and the Malmquist index model to evaluate the efficiency of government healthcare expenditures in Hubei Province. It aims to enhance the author's understanding of applied mathematics, enrich practical experience, and provide innovative insights for future mathematical studies.

2. Research Design

This study examines the efficiency of government healthcare expenditure, focusing on how effectively government funding generates medical resources through output-oriented scale efficiency and technical efficiency. Using the DEA-Malmquist index analysis, total factor productivity is decomposed into pure technical efficiency and scale efficiency, reflecting the overall efficiency of Hubei's healthcare expenditures. Pure technical efficiency measures the maximum output from a given level of input, indicating how it affects the comprehensive efficiency of healthcare expenditure. This metric sheds light on the government's budgeting efficiency and resource planning capabilities. In contrast, scale efficiency assess how well the scale of Hubei's healthcare expenditure is optimized.

The DEA-Malmquist index model is an advanced version of the traditional DEA method, commonly applied in assessing production efficiency in finance, industry and medical fields. While the traditional DEA model accurately captures static input-output efficiency, it falls short in analyzing time series data, as the efficiency values from different years are not directly comparable. This limitation prevents the traditional DEA method from reflecting changes in efficiency over various periods [5]. Based on the research of Wang Baoshun and Fan Miao, this paper uses the Malmquist index model to study the pure technical efficiency (BPC), scale efficiency (SECH),technological progress (TECH), and changes in total factor productivity (TFPCH) acriss 15 DMUs from 2008 to 2022 [6-7]. The istence of n DMUs, each using m types of inputs to produce s types of output in period t. Let x_j^t and y_j^t represent the input and output values for DMU j个in period t, where both values are positive, and t=1,2,.....,T. Assuming constant returns to scale, the distance functions for each DMU in period t and t+1 are denoted as follows: In period t: $D_C^t(x^t,y^t)$and in period t+1: $D_C^{t+1}(x^t,y^t)$. In period t: $D_C^t(x^{t+1},y^{t+1})$and in period t+1: $D_C^{t+1}(x^{t+1},y^{t+1})$. Thus, the change in technical efficiency from period t to t+1, under the technology of period t, is calculated as:

$$M^t=\frac{D_C^t(x^{t+1},y^{t+1})}{D_C^t(x^t,y^t)} \tag{1}$$

Under the technology of period t+1, the change is:

$$M^{t+1}=\frac{D_C^{t+1}(x^{t+1},y^{t+1})}{D_C^{t+1}(x^t,y^t)} \tag{2}$$

The (Total Factor Productivity Change) from t to t+1is obtained by calculating the geometric mean of the two efficiency changes, as shown below:

$$M(x^t,y^t,x^{t+1},y^{t+1})=(M^t*M^{t+1})^{\frac{1}{2}}=\left[\frac{D_C^t(x^{t+1},y^{t+1})}{D_C^t(x^t,y^t)}*\frac{D_C^{t+1}(x^{t+1},y^{t+1})}{D_C^{t+1}(x^t,y^t)}\right]^{\frac{1}{2}} \tag{3}$$

Table 1 below provides the interpretation of each index in the DEA-Malmquist model. Using these model formulas, this study will conduct a quantitative analysis of the data, interpreting each index in the context of the research objectives.

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Table 1: DEA—Malmquist index model

Index Name	Interpretation
Total Factor Productivity (TFPCH)	A TFPCH>1 indicates improved productivity fro period t to t+1;a TFPCH<1 indicates a decline.
Pure Technical Efficiency (BPC)	A BPC>1 suggests that increased technical efficiency positive impacts productivity; BPC<1 indicates a restraining effect.
Scale Efficiency (SECH)	A SECH>1 implies that scale expansion enhances productivity; SECH<1 implies a restraining effect.
Technological Progress (TECH)	A TECH>1 indicates technological advancement and efficiency gains; TECH<1 indicates a decline in both.

2.1. Data and Variable Selection

This study collected and organized data from the National Bureau of Statistics, including the *China Statistical Yearbook* (2018–2023), *China Health Statistical Yearbook* (2008–2015), *China Health and Family Planning Statistical Yearbook* (2016–2017), *China Health and Wellness Statistical Yearbook* (2018–2022), and *China Social Statistical Yearbook* (2022–2023). These sources provided a time-series dataset on Hubei Province's healthcare sector from 2008 to 2022, including 15 DMUs and a total of 120 data samples for empirical analysis. Following the methods of Jin R. and Li Y., the study prioritizes relevance and comparability in selecting healthcare indicators for the DEA-Malmquist index analysis of Hubei's healthcare expenditure efficiency [8-9].

Input Indicators are capturing financial and resource allocation aspects, and the variables include: a1 (government health care expenditure): local government healthcare funding (billion CNY), a2 (number of healthcare institutions): Total count of healthcare facilities (hospitals, clinics, etc.), and a3 (Number of healthcare technical personnel): Licensed medical professionals and technical staff in ten thousand people. Output Indicators are focusing on public health outcomes and healthcare efficiency. The variables include: b1 (Maternal mortality rate): Deaths per 100,000 live births, an indicator of maternal and infant health, b2 (Incidence rate of Class A and B infectious diseases): Cases per 100,000 population, indicating public health levels, b3 (Hospital bed utilization rate): Utilization rate of hospital beds, higher rates suggest greater efficiency, and b5 (Hospital bed utilization rate): utilization rate of hospital beds, higher rates suggest greater efficiency. Input indicators cover four dimensions—financial supply, resource allocation, human capital, and social security—to analyze healthcare expenditure efficiency. Government healthcare expenditure reflects investment in healthcare management, services, insurance, preventive care, supervision, maternal care, and rural health. And output indicators address public health outcomes and healthcare efficiency. The maternal mortality and infectious disease incidence rates are internationally recognized indicators of socioeconomic and healthcare quality. Hospital bed utilization reflects bed use efficiency, while average outpatient and inpatient medical expenses serve as performance metrics in public hospital assessments, highlighting patient cost burden and healthcare service quality.

3. Analysis

To assess the efficiency of healthcare expenditures in Hubei Province, data spanning 2008-2022 were compiled, with missing values filled through linear interpolation to retain sample completeness. Reverse indicators, including b1,b2,b4,and b5 were treated by taking reciprocals, yielding the dataset for this study, (Table 2).

Applying the DEA—Malmquist index model to these variables produced data reflecting the efficiency of government healthcare spending in Hubei Province (Table 2). Analysis reveals that 2012

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marked a pivotal point in Hubei's healthcare resource allocation. Between 2008 and 2012, resource allocation efficiency remained high, with pure technical efficiency consistently at "1." However, scale efficiency was low, resulting in an overall low efficiency score.

Table 2: Time-Series Data for DEA—Malmquist Index Model

	Input			Output				
year	a1	a2	a3	b1	b2	b3	b4	b5
2022	799.47	36782	46.86	7.20	107.95	77.19	302.20	10747.50
2021	706.33	36529	45.64	8.60	199.38	78.90	291.80	11224.10
2020	1019.71	35447	42.85	10.00	290.81	72.09	293.80	11738.50
2019	601.82	35515	41.62	7.09	239.82	92.30	259.60	10233.90
2018	575.74	36486	41.1	9.69	250.75	92.69	238.70	9556.50
2017	614.69	36357	39.97	9.60	249.83	92.69	226.60	9004.70
2016	588.9	36354	38.45	8.60	249.92	92.00	221.20	8662.20
2015	515.25	36179	36.79	9.10	251.55	92.40	212.70	8124.00
2014	401.32	36077	33.56	9.00	246.85	96.09	204.70	7678.30
2013	322.08	35631	30.93	11.60	254.81	96.50	189.80	7303.50
2012	267.99	35240	28.87	10.10	264.73	99.30	178.00	6699.00
2011	247.30	35625	26.81	10.60	280.35	98.69	167.00	6243.20
2010	179.13	34269	25.58	15.40	278.59	96.09	153.80	5735.20
2009	139.24	32790	24.7	17.70	314.03	92.69	145.77	5114.41
2008	95.08	10305	23.38	17.29	314.89	87.30	133.30	4636.10
2007	66.11	11093	22.71	20.02	310.32	81.90	126.60	4599.00

Insights from the 2010 Hubei Health Development Report indicate that this period saw a strategic shift by the provincial government from widespread establishment of community and primary healthcare facilities to a more moderated approach, optimizing the number and structure of institutions. In 2010, Hubei closed 229 substandard healthcare facilities while increasing bed capacity by 13,351, signaling an improvement in resource management. Additionally, the government integrated specialist hospitals and community clinics and enhanced village health facilities, expanding infrastructure significantly between 2010 and 2011. Consequently, by 2011, comprehensive efficiency achieved "effectiveness." Between 2013 and 2019, both pure technical efficiency and scale efficiency oscillated within the range of 0.98-1.03, with the comprehensive efficiency index ("TEPCH") balancing at the threshold of effectiveness. Significant efficiency improvements were noted in 2014, 2016, and 2019, where pure technical efficiency and scale efficiency exceeded "1" in most cases, indicating improved healthcare management practices and infrastructure. The only exception was 2016, where the scale efficiency value was slightly below "1" at 0.9999. The fluctuations in pure technical efficiency may correlate with regional economic disparities, as central China (including Hubei) tends to lag behind eastern China in healthcare management expertise and technological advancements. Additionally, the slower pace of healthcare market reform in Hubei has hindered local competition and sectoral efficiency. The 2011 national two-child policy, which significantly increased healthcare resource utilization in eastern regions, had a relatively limited impact in Hubei and other central/western provinces, where it primarily slowed the decline in child dependency ratios rather than boosting healthcare demand significantly.

These findings underscore that scientific and effective allocation of healthcare resources, alongside a rational scale of government healthcare expenditure, are essential factors in enhancing efficiency in healthcare spending.

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Table 3: Healthcare Expenditure Efficiency of the Hubei Provincial Government

Year	TFPCH	Technical Efficiency	BPC	SECH
2008	1.0000	1.0000	1.0000	1.0000
2009	0.9961	1.0000	1.0000	0.9961
2010	0.9994	1.0000	1.0000	0.9994
2011	1.0045	1.0000	1.0000	1.0045
2012	0.9994	1.0000	1.0000	0.9994
2013	0.9666	1.0000	0.9856	0.9808
2014	1.0266	1.0000	1.0108	1.0157
2015	0.9794	1.0000	0.9758	1.0037
2016	1.0024	1.0000	1.0025	0.9999
2017	0.9783	1.0000	0.9954	0.9828
2018	0.9982	1.0000	0.9985	0.9997
2019	1.0517	1.0000	1.0325	1.0186
2020	0.9172	1.0000	0.9439	0.9717
2021	1.0414	1.0000	1.0228	1.0182
2022	1.0470	1.0000	1.0358	1.0108

As shown in Table 3, the comparison of Total Factor Productivity (TFPCH), Pure Technical Efficiency (BPC), and Scale Efficiency (SECH) through DEA–Malmquist Index analysis shows significant fluctuation in Hubei Province's government healthcare expenditure efficiency from 2019 to 2022. After years of healthcare system reforms, 2019 marked substantial progress in Hubei's healthcare expenditure efficiency, with effective resource allocation and scaling. However, the outbreak of the pandemic in 2020 created an unexpected shortage of healthcare resources, with available beds and medical staff failing to meet demand. Consequently, healthcare expenditure efficiency dropped to its lowest point in 15 years. With robust support from the national government and other provinces, Hubei managed to rebound post-pandemic, achieving rapid improvement in healthcare efficiency by 2021. In subsequent years, the provincial government significantly increased its fiscal support for healthcare, especially in scaling and advancing medical technology in city-level hospitals. By 2022, Hubei had nine city-level hospitals ranked in the national top 100, demonstrating the success of optimized healthcare resource allocation. Overall, the Hubei provincial government has effectively enhanced healthcare expenditure efficiency by optimizing resource allocation and scaling up healthcare expenditure (Figure 1).

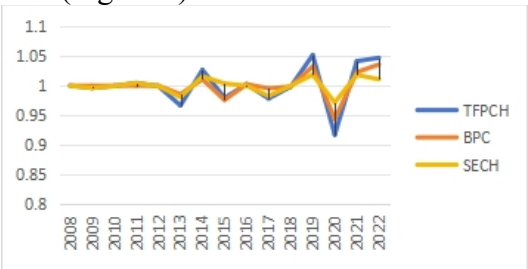

Figure 1: Comparison of healthcare expenditure efficiency in Hubei Province (2008-2022)

4. Conclusion

The scale of healthcare expenditure in Hubei Province remains insufficient, and the scientific effectiveness of resource allocation alongside a reasonable scale of government healthcare

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expenditure are key factors in enhancing expenditure efficiency. Between 2008 and 2012, Hubei's healthcare resource allocation efficiency was relatively high, with a pure technical efficiency consistently at "1." However, scale efficiency remained low, resulting in suboptimal overall efficiency. From 2013 to 2019, pure technical efficiency and scale efficiency fluctuated between 0.98 and 1.03, with comprehensive efficiency levels oscillating near the threshold of effectiveness. Between 2019 and 2022, fluctuations in Hubei's healthcare expenditure efficiency intensified. In 2019, overall efficiency rose significantly, with both resource allocation and healthcare scale showing improved effectiveness. However, the onset of the pandemic in 2020 interrupted this upward trend; healthcare resources in Hubei became strained, with medical personnel and bed capacity unable to meet rising demands. Consequently, comprehensive efficiency in government healthcare expenditure fell sharply to its lowest level in nearly 15 years. By 2021, Hubei saw a swift improvement in efficiency, returning to pre-pandemic levels by 2022. Based on this applied research, the author concludes that applying mathematical concepts to real-world problem analysis clarifies problem-solving approaches, enhancing systematic understanding of essential properties and trends in practical issues. This approach enables the accurate extraction of mathematical characteristics from real-world problems, facilitating the selection and development of more suitable mathematical models for empirical analysis. The author believes that mathematical model analysis rooted in applied mathematics promotes problem visualization, offering a comprehensive view of both problem context and phenomena, which proves highly beneficial for their own mathematical learning.

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