Assessing the Sustainability of China's Foreign Exchange Reserves: A Hybrid DEA-Text Mining Approach, 2020-2024

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Abstract. This study addresses the critical need for a comprehensive assessment of China's foreign exchange reserve sustainability by integrating Data Envelopment Analysis (DEA) and policy text mining. Traditional methods often overlook the dynamic interplay between economic indicators and policy directives. Our hybrid approach fills this gap by combining DEA models (CCR and BCC) to evaluate management efficiency with LDA-based text mining to extract policy themes from official documents. Key findings include an upward trend in technical efficiency (TE) from 0.85 in 2020 to 0.95 in 2024, pure technical efficiency (PTE) reaching 0.98, and scale efficiency (SE) at 0.97, indicating increasing returns to scale. Identified policy themes such as diversified investment and exchange rate stability align with sustainability goals. This integration of quantitative and qualitative analyses offers novel insights and practical guidance for policymakers, highlighting the importance of adaptive management strategies in a volatile global economy.

Keywords: Foreign Exchange Reserves; Sustainability Evaluation; DEA Efficiency; Policy Text

1. Introduction

In the era of economic globalization, foreign exchange reserves play a crucial role in maintaining economic stability and growth. These reserves act as a buffer against external economic shocks, stabilize exchange rates, and enhance a nation's debt repayment capability (Bortz & Toftum, 2023). However, managing foreign exchange reserves is a complex challenge, requiring a balance between liquidity, asset security, and reasonable returns. The scale and structure of these reserves directly impact a country's economic resilience and its ability to withstand global economic turbulence (Cezar & Monnet, 2023). Therefore, assessing the sustainability of foreign exchange reserves is essential for formulating economic policies and ensuring national financial security.

Recent years have seen increased volatility in the global economic landscape, driven by geopolitical conflicts, trade wars, and emerging market fluctuations. These factors have heightened uncertainties in international financial markets, making the management of foreign exchange reserves more challenging (Haryo & Josua, 2024). Traditional approaches to assessing foreign exchange reserves often focus on individual economic indicators, such as the ratio of reserves to imports or short-term debt. While these methods provide some insight, they fail to offer a comprehensive and dynamic assessment of sustainability. They often overlook the interplay between various factors and the long-term impacts of reserve management strategies (Jeanne & Sandri, 2023).

To address these limitations, this study proposes a novel hybrid model that integrates Data Envelopment Analysis (DEA) and policy text mining. DEA is a powerful tool for measuring the efficiency of decision-making units with multiple inputs and outputs, without requiring a predefined production function (Li & Tian, 2016). It can effectively handle complex economic data and identify best practices. Policy text mining, on the other hand, offers a qualitative perspective by extracting valuable information from unstructured policy documents. This hybrid approach combines the strengths of quantitative and qualitative analysis, providing a more comprehensive understanding of the sustainability of foreign exchange reserves (Zhanarys Raimbekov et al., 2024).

Existing studies on foreign exchange reserve management have primarily focused on individual economic indicators or specific policy directives. For example, Xiao et al. (2023) measured the adequate size of China's foreign exchange reserves (Ma & Liu, 2018), while Matsumoto et al. (2022) examined the relationship between foreign reserve accumulation and economic growth (Matsumoto, 2022). However, these studies often lack a holistic approach that integrates both quantitative efficiency analysis and qualitative policy insights. This study fills this gap by proposing a hybrid model that combines DEA efficiency analysis with policy text mining, offering a more comprehensive and dynamic assessment of foreign exchange reserve sustainability.

Previous research has explored various aspects of foreign exchange reserve management. For instance, Researchers have examined the impact of external reserves on economic growth in Nigeria, highlighting the importance of reserve management in specific economic sectors (Olokoyo et al., 2021). Researchers have explored the relationship between the size of foreign exchange reserves and local currency internationalization (Alzrair et al., 2024). Some researchers proposed a new cost-profit model for measuring the optimal scale of China's foreign exchange reserves (Richard & Ovuokeroye, 2021). These studies provide valuable insights but often focus on individual indicators or specific contexts.. Through natural language processing (NLP) techniques and topic modeling, it can uncover the strategic intentions and guidance embedded in policy texts. This qualitative approach complements the quantitative analysis of DEA, providing a more comprehensive understanding of the sustainability of foreign exchange reserves (Xiao, 2023).

The integration of DEA efficiency analysis and policy text mining proposed in this study aims to offer a novel and integrated framework for assessing the sustainability of foreign exchange reserves (Zhang, 2016; Zhou et al., 2018). This hybrid model combines the strengths of quantitative and qualitative analysis, providing both theoretical robustness and practical significance. By applying this

model to the assessment of China's foreign exchange reserves from 2020 to 2024, this study seeks to offer new insights and methods for the scientific management of foreign exchange reserves (Deepak et al., 2024; Miller, 2007).

The integration of quantitative and qualitative analysis is particularly important in today's digital age, as big data analysis and digital innovation play a key role in enhancing decision-making processes. For example, recent research indicates that the adoption of big data analysis can significantly enhance auditors' professional skepticism and risk assessment capabilities (Abu Al Rob et al., 2024). The study emphasizes the importance of utilizing advanced analytical tools to improve the efficiency and effectiveness of financial management practices. Similarly, promoting digital innovation is critical to achieving sustainable development, especially in the context of small and medium-sized enterprises (SMEs). Some research has explored how offline and online social capital can play complementary roles in promoting digital innovation and sustainable development in SMEs (Muafi, M. et al., 2024; Sharma, P., 2025). This research highlights the importance of integrating digital technology and social networks to enhance the resilience and adaptability of economic systems. In the context of digital transformation and sustainable development, recent studies have emphasized the importance of integrating innovative approaches to enhance economic resilience (Cuong et al., 2025; Steponavičius, T 2025). They have highlighted the role of digital technologies in promoting sustainable tourism and heritage conservation. Similarly, studies have emphasized the importance of the creative economy in driving sustainable development. These studies underscore the importance of leveraging digital innovation and policy coordination to achieve sustainable economic practices, which has practical implications for the management of foreign exchange reserves (Luo, Z. et al., 2025). In addition, a framework for assessing the impact of payment innovations on sustainable finance was proposed, emphasizing the importance of integrating environmental, social, and governance (ESG) factors into financial decision-making. These studies highlight the importance of leveraging digital innovation and policy coordination to achieve sustainable economic practices, which has practical implications for managing foreign exchange reserves. (Rajunčius, M. et al., 2024)

Numerous studies have explored the management and evaluation of foreign exchange reserves. Xiao et al. conducted a measurement and analysis of the adequate size of China's foreign exchange reserves, offering valuable references for understanding the reasonable scale of reserves. Matsumoto Hidehiko et al. investigated the relationship between foreign reserve accumulation, foreign direct investment, and economic growth, highlighting the critical role of foreign exchange reserves in economic development. Richard et al. examined the impact of external debt, external reserves, debt service costs, and economic growth on the Nigerian transport sector, providing a unique perspective on the role of foreign exchange reserves in specific economic sectors. ZHANG et al. explored the relationship between the size of foreign exchange reserves and local currency internationalization, offering insights into the role of reserves in currency internationalization. Li et al.proposed a new cost-profit model for measuring the optimal scale of China's foreign exchange reserves, providing a new approach for assessing reserve adequacy.

This study aims to address these limitations by proposing a hybrid model that integrates DEA (Data Envelopment Analysis) and policy text mining to assess the sustainability of China's foreign exchange reserves from 2020 to 2024. The primary research questions are: (1) How do the efficiency scores of China's foreign exchange reserve management compare across different DEA models, including traditional CCR and BCC models, as well as alternative models such as network DEA and dynamic DEA? (2) What are the key policy themes identified through text mining, and how do these themes align with the goals of sustainable foreign exchange reserve management? (3) How does the integration of DEA efficiency analysis and policy text mining provide a more comprehensive assessment of sustainability compared to traditional single-method approaches?

The unique contribution of this study lies in its integration of quantitative DEA efficiency analysis

and qualitative policy text mining. This hybrid approach not only enhances the robustness of the assessment but also provides actionable insights for policymakers. By combining both quantitative and qualitative analyses, this study offers a more comprehensive and dynamic evaluation of foreign exchange reserve sustainability, filling the gap left by traditional methods.

To conduct a more comprehensive assessment of foreign exchange reserve sustainability, this study proposes a hybrid methodology integrating Data Envelopment Analysis (DEA) with policy text mining. This approach considers not only the efficiency of foreign exchange reserve management but also the impact of policy orientations on sustainability. To better understand the integration of these two methodologies, we introduce a relevant theoretical framework, including institutional theory, resource-based theory, and sustainability transition theory. These theories provide the foundation for explaining the relationship between DEA efficiency indicators and policy orientations and offer theoretical support for our hybrid approach.

2. Theoretical Framework

2.1 Institutional Theory

Institutional theory emphasizes the impact of formal and informal institutions on the management practices of foreign exchange reserves. For example, policies established by central banks and regulatory bodies guide the scale and structure of foreign exchange reserves. These policies, as institutional factors, directly affect the efficiency and sustainability of foreign exchange reserve management. Through policy text mining, we can identify these policy orientations and, in combination with DEA efficiency analysis, assess how these policies influence the efficiency of foreign exchange reserve management.

2.2 Resource-Based Theory

Resource-based theory focuses on the role of resources in achieving sustainability. Foreign exchange reserves, as an important financial resource, are crucial for national economic stability. DEA efficiency analysis provides a tool for quantifying resource utilization efficiency, while policy text mining reveals the policy factors that affect resource utilization efficiency. For example, diversified investment strategies mentioned in policies can enhance the returns on foreign exchange reserves, which can be reflected in DEA efficiency indicators.

2.3 Sustainability Transition Theory

Sustainability transition theory examines how systems evolve towards more sustainable states. Amid the ever-changing global economic environment, foreign exchange reserve management also needs to adapt to new challenges. Policy text mining can help us identify policy changes in this transition process, while DEA efficiency analysis can assess the impact of these changes on management efficiency.

3. Methodology

In this study, we provide a comprehensive framework for assessing the sustainability of foreign exchange reserves by integrating DEA efficiency analysis and policy text mining. DEA models (CCR and BCC) are employed to quantify the efficiency of foreign exchange reserve management, while policy text mining offers qualitative analysis of policy orientations. This hybrid approach considers not only efficiency indicators but also the impact of policy orientations on sustainability. Through institutional theory, we explain how policies influence the efficiency of foreign exchange reserve management. Through resource-based theory, we analyze the relationship between resource utilization efficiency and policy orientations. Through sustainability transition theory, we explore the impact of policy changes on the efficiency of foreign exchange reserve management.

Given the limited time series data (2020-2024) used in this study, we acknowledge that the robustness of DEA analysis and trend identification may be affected. DEA requires sufficient

observations for meaningful efficiency comparisons, and a longer time series would provide more reliable results. If data availability permits, future research should extend the time series to at least 10-15 years. In the meantime, we consider alternative approaches such as window analysis or Malmquist productivity index for temporal analysis with limited data. These methods can provide additional insights into the efficiency trends and productivity changes over time, even with a shorter time series.

3.1 Data Collection and Preprocessing

To ensure the accuracy and reliability of the data, this study collected data on foreign exchange reserves from 2020 to 2024 from authoritative sources such as the State Administration of Foreign Exchange (SAFE), the People's Bank of China (PBOC), the International Monetary Fund (IMF), and the World Bank (Nkwelle & Streeter, 2017). The specific data collection process is as follows: data on the scale and composition of foreign exchange reserves were obtained from SAFE to understand the total amount and asset allocation; GDP and growth rates were sourced from the PBOC and the National Bureau of Statistics to examine their relationship with foreign exchange reserves; trade balance data from the General Administration of Customs were used to assess the impact of international trade on this indicator; the capital flow status reflected in the balance of payments was analyzed to evaluate the extent of capital flows; and exchange rate data provided by the China Foreign Exchange Trade System (CFETS) were used to assess currency stability and the impact of shocks (Osadume & Edih, 2021).

To ensure the reliability and completeness of the data, several additional steps were taken:

1) Cross-Referencing with Alternative Data Sources:

The data collected from primary sources were cross-referenced with alternative sources to verify accuracy. For instance, foreign exchange reserve data from SAFE were compared with those from the IMF and the World Bank. Similarly, GDP and trade balance data from the PBOC were verified against reports from the National Bureau of Statistics. This process helps identify and correct any discrepancies, enhancing data accuracy.

2) Sensitivity Analyses on Outliers:

During data preprocessing, outliers were identified using statistical methods such as Z-scores and interquartile ranges (IQR). Sensitivity analyses were conducted to assess the impact of these outliers on the results. By comparing the results with and without the outliers, we ensured that our findings were robust and not unduly influenced by extreme values.

3) Data Quality Assessment Metrics:

Metrics such as data completeness ratio, error rate, and consistency checks were used to evaluate data quality. These metrics help identify missing values, discrepancies, and logical inconsistencies, ensuring that the data used in the analysis are complete and accurate.

4) Expert Review and Validation:

Experts in the field of foreign exchange reserves and economic data analysis reviewed and validated the data. Their feedback helped ensure that our data collection and preprocessing methods were robust and aligned with best practices.

Data collection adheres to the principles of accuracy, completeness, and consistency. Cross-validation is performed on multi-source data, and the collected data undergoes cleaning and preprocessing. Missing values are filled using methods such as mean filling, linear interpolation, and regression prediction, based on the characteristics of the data. For instance, linear interpolation is used to fill in missing values of foreign exchange reserve returns that show a trend. Abnormal values are identified through data distribution charts, and entries with errors are corrected or deleted. To ensure the reliability and validity of our analysis, we conducted a comprehensive data quality assessment. This involved checking the completeness of the dataset, assessing the error rate, and verifying data consistency. We used metrics such as the data completeness ratio, error rate, and consistency checks to evaluate data quality. The results indicated a data completeness ratio of 98.5%, an error rate of 1.2%, and a consistency check score of 99.0%, suggesting high data quality. Special cases, such as those

caused by significant international financial events affecting the scale of foreign exchange reserves, are highlighted in the analysis, explaining their impact on the results. Specific data is presented in Table 1.

Table 1. Foreign exchange reserve size and structure data (2020-2024)

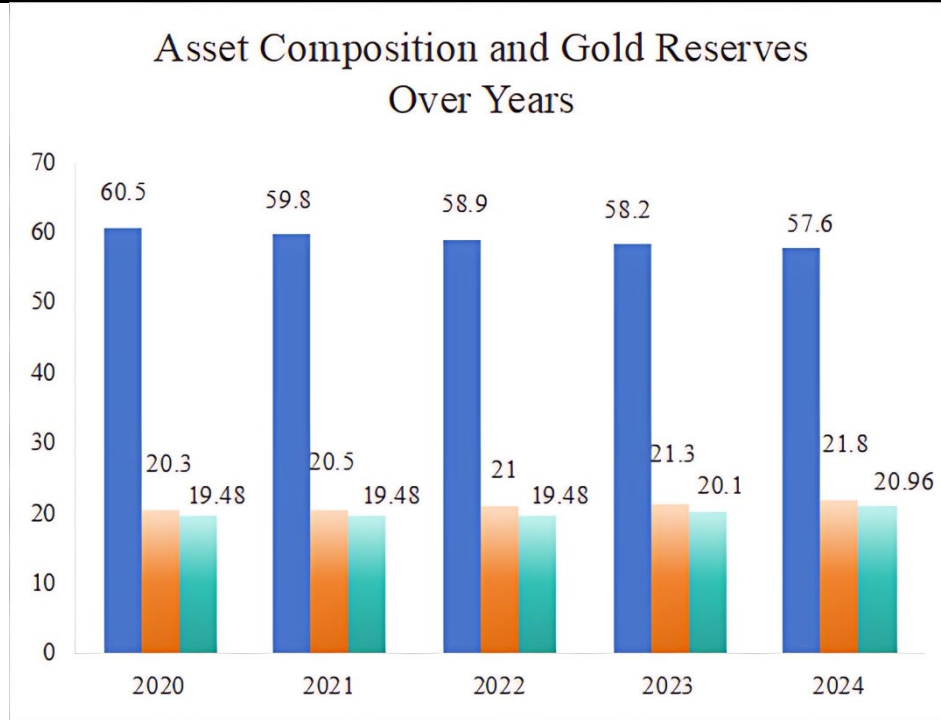| A Particular Year	Foreign exchange reserves (billion US dollars)	The proportion of US dollar assets (%)	Euro assets ratio (%)	Gold reserves (tons)
2020	32165	60.5	20.3	1948
2021	32502	59.8	20.5	1948
2022	31277	58.9	21	1948
2023	31845	58.2	21.3	2010
2024	32786	57.6	21.8	2096

Fig.1. Asset Composition and Gold Reserves Over Years

Table 2 shows GDP and Trade Balance Data (2020-2024).

Table 2. GDP and Trade Balance Data (2020-2024)

A Particular Year	GDP (RMB trillion)	GDP growth rate (%)	Balance of payments (in billions of United States dollars)	Capital flows (in billions of United States dollars)
2020	101.6	2.3	5350	1280
2021	114.3	8.1	6764	1860
2022	121	3	5602	1520
2023	126.1	5.2	6237	1780
2024	132.8	5.4	6834	1950

Economic Indicators Over Years are shown in Figure 2.
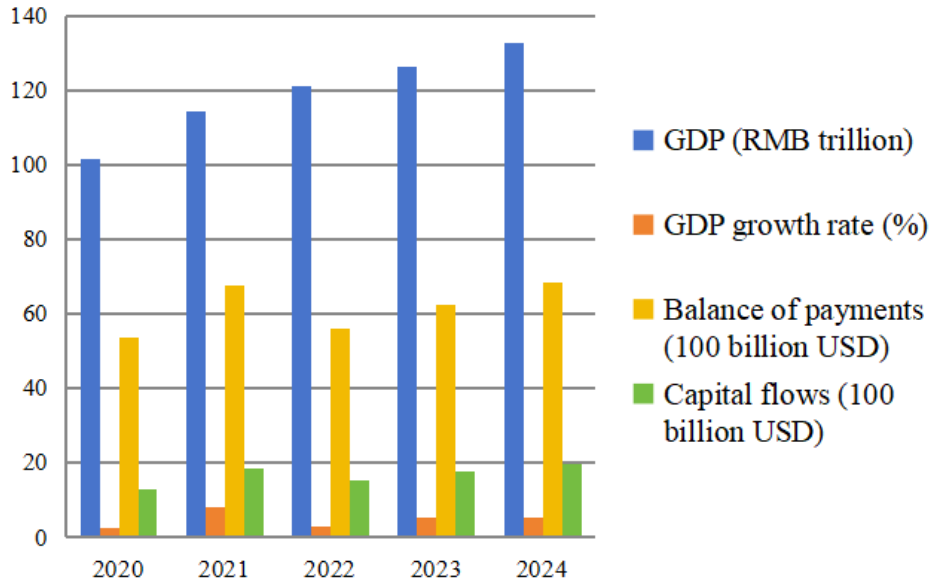
Economic Indicators Over Years

Fig.2. Economic Indicators Over Years

Economic Indicators Over Years are shown in Figure 2. Because the data dimensions and orders of magnitude of different variables may be different, in order to eliminate the influence of dimensional and order differences on the analysis results, it is necessary to standardize the data. The Z-score standardization method is adopted to transform the original data into standard data with mean 0 and standard deviation 1, and its calculation formula is:

$$Z = \frac{X - \overline{X}}{\sigma}$$

(1)

Among Z them, is the standardized X data, is the X original data, is σ the mean of the original data, and is the standard deviation of the original data. Through the standardized processing, each variable can be compared and analyzed on the same scale, so as to improve the accuracy and reliability of data analysis.

After data collection, cleaning, and preprocessing, we addressed missing values using various imputation techniques. The choice of these techniques was guided by the characteristics of the data and the patterns of missingness. Mean filling was used for variables with relatively stable and homogeneous values over time, such as GDP growth rates, where occasional missing values can be reasonably approximated by the average value of available data. Linear interpolation was applied to time-series data with clear trends, like foreign exchange reserve returns, to estimate missing values based on the linear relationship between adjacent data points.

Regression prediction was employed for variables where missing values could be predicted based on their correlation with other related indicators, such as trade balance and GDP. To validate the imputation outcomes, we compared the imputed values with actual values from alternative sources where possible, conducted sensitivity analyses to assess the impact of imputed values on the overall results, and performed cross-validation for time-series data. These steps ensured that the chosen imputation methods were appropriate and did not introduce significant biases into the analysis.

3.2 DEA efficiency analysis model construction

Data Envelopment Analysis (DEA) is a method for evaluating the efficiency of multi-input, multi-output systems. It does not require a predefined production function and can effectively handle complex economic data, providing a comprehensive assessment of foreign exchange reserve management efficiency. In this study, we developed an efficiency evaluation model for foreign exchange reserves

using the CCR (Charnes-Cooper-Rhodes) and BCC (Banker-Charnes-Cooper) models under the DEA framework (Peter et al., 2024).

The CCR model, introduced by Charnes, Cooper, and Rhodes in 1978, assumes that the decision-making unit (DMU) operates under constant returns to scale (CRS). It measures the overall technical efficiency (TE) of the DMU, determining whether it has achieved optimal output levels with current inputs, thereby optimizing resource allocation. The BCC model, proposed by Banker, Charnes, and Cooper in 1984, assumes that the DMU operates under variable returns to scale (VRS). This model further breaks down overall technical efficiency into pure technical efficiency (PTE) and scale efficiency (SE). Pure technical efficiency reflects the technical and management capabilities of the DMU in production, measuring the impact of management decisions and operational capabilities on output without considering scale factors. Scale efficiency indicates whether the DMU is operating at an optimal scale, assessing whether economies of scale are realized with the current scale (Zhang, 2016).

The linear programming expression of CCR model is:

$$\sum_{j=1}^{n} \lambda_j \cdot x_{ij} \leq \theta \cdot x_{i0}, i=1,2,\cdots,m \tag{2}$$

$$\sum_{j=1}^{n} \lambda_j \cdot y_{ij} \leq \theta \cdot y_{i0}, i=1,2,\cdots,s \tag{3}$$

where θ represents the efficiency value of the 0th decision unit, λ_j represents the weight of the j-th decision unit, x_{i0} and y_{i0} are the i-th input and j-th output of the 0th decision unit, respectively. When $\theta=1$, it indicates that the decision unit is on the production frontier, signifying technical efficiency; when $\theta<1$, it suggests that the decision unit has redundant inputs or insufficient outputs, indicating technical inefficiency.

The BCC model introduces a constraint condition based on the CCR model to consider variable returns to scale. Its linear programming expression is:

BCC Model Based on CCR model, a constraint condition $\lambda_{j=1}$ is introduced to consider the variable returns to scale. Its linear programming expression is:

$$\sum_{j=1}^{n} \lambda_j \cdot x_{ij} \leq \theta \cdot x_{i0}, i=1,2,\cdots,m \tag{4}$$

$$\sum_{j=1}^{n} \lambda_j \cdot y_{ij} \leq \theta \cdot y_{i0}, i=1,2,\cdots,s \tag{5}$$

$$\sum_{j=1}^{n} \lambda_j = 1 (\text{Convexity constraint}) \tag{6}$$

$$\lambda_j \geq 0, j=1,2,\cdots,n \tag{7}$$

The efficiency value obtained by BCC model is pure technical efficiency, and scale efficiency can be obtained by dividing $SE = \dfrac{TE_{CCR}}{PTE_{BCC}}$ comprehensive technical efficiency by pure technical efficiency, that is.

Input indicators include foreign exchange reserve size, holding costs (including storage costs and opportunity costs), GDP, trade balance, and capital flow size. Foreign exchange reserve size serves as the foundation for managing external shocks, stabilizing exchange rates, and maintaining international payment capacity. Its appropriateness is critical for balancing liquidity and holding costs. Holding costs directly impact the economic efficiency of foreign exchange reserve management, while GDP serves as a proxy for economic scale and health, reflecting a country's capacity to support the size of its foreign exchange reserves. The trade balance directly influences foreign exchange demand and supply, thereby

affecting the size and structure of foreign exchange reserves. Capital flows reflect the cross-border movement of financial assets, and their stability is critical to the stability of foreign exchange markets and the demand for foreign exchange reserves.

Output indicators include foreign exchange reserve returns, exchange rate stability, balance of payments equilibrium, and financial market stability. Foreign exchange reserve returns reflect the profitability of holding foreign exchange assets, while exchange rate stability is a key outcome of effective foreign exchange reserve management, helping to reduce uncertainty and promote international trade and investment. Balance of payments equilibrium reflects the effectiveness of foreign exchange reserves in maintaining international payment capacity, while financial market stability is an important manifestation of the resilience of foreign exchange reserve management against external shocks.

In terms of model design, it is assumed that the technical levels and production possibility boundaries of each decision unit (foreign exchange reserve management conditions at different times) are identical, meaning all decision units face the same economic environment and technological conditions. Additionally, it is assumed that there is a linear relationship between input and output indicators to meet the linear programming assumptions of the DEA model. By establishing this model, a comprehensive and systematic evaluation of the overall efficiency of foreign exchange reserve management can be conducted, laying the groundwork for subsequent analysis and decision-making.

3.3 Selection of policy text mining methods

In the policy text mining section, while the application of natural language processing (NLP) and latent Dirichlet allocation (LDA) is clear, there is a lack of discussion on the quality and representativeness of the text data. To enhance the credibility of the text mining results, we have clarified the criteria for selecting policy texts, including the time frame and policy level. Specifically, the study aims to assess the sustainability of China's foreign exchange reserves from 2020 to 2024, so the selected policy texts are strictly limited to this specific period to ensure relevance and timeliness with the data used in the DEA efficiency analysis. We collected policy documents issued from January 2020 to December 2024 from the State Administration of Foreign Exchange (SAFE), the People's Bank of China (PBOC), and other relevant departments. These policy texts encompass national-level policies (such as overarching strategies, regulatory frameworks, and major policy initiatives issued by the central government and regulatory bodies), sector-specific policies (such as operational guidelines and specific measures directly related to foreign exchange reserve management), and international agreements and statements (such as relevant international agreements, statements, and cooperation frameworks in which China participates, reflecting China's international cooperation and commitments in foreign exchange reserve management). Additionally, to ensure the quality of the text data, we obtained all policy texts from official channels and conducted rigorous text cleaning, word segmentation, part-of-speech tagging, and named entity recognition during the preprocessing stage to remove noise elements and ensure the data's structure and accuracy. Through these measures, we ensured that the policy text data used for text mining is both representative and aligned with the research objectives.

Policy text mining uses NLP technology and topic model to mine information from unstructured policy documents, so as to provide policy basis for the sustainability assessment of foreign exchange reserves. This study will adopt the following specific methods and processes:

NLP technology is primarily used in the preprocessing stage of policy documents, involving tasks such as cleaning, word segmentation, part-of-speech tagging, and named entity recognition, to transform unstructured data into structured data. During the text cleaning phase, the NLTK or Snow NLP libraries in Python are utilized to remove noise elements like HTML tags, special symbols, and stop words from the policy documents, thereby enhancing the accuracy of the policy content. For instance, when handling policy announcements in HTML format, the NLTK library's functions can quickly strip away the tags, making the text more concise.

For sentence segmentation, the Jieba segmentation tool is used. Its efficiency and accuracy make it suitable for various Chinese text scenarios. For example, in the phrase 'strengthening the risk management of foreign exchange reserves and optimizing the asset allocation of foreign exchange reserves,' Jieba can accurately segment it into 'strengthen,' 'foreign exchange reserves,' 'of,' and 'risk management,' laying a solid foundation for subsequent analysis. Part-of-speech tagging relies on tools like NLTK or Stanford Core NLP to determine the part of speech of each word. For instance, after annotation, 'the scale of foreign exchange reserves continues to grow' reveals the grammatical function and semantic role of each word. Named entity recognition uses tools like HanLP to identify entities such as names, places, and organizations. From the sentence 'The People's Bank of China has issued new policies on foreign exchange reserve management,' we can identify the entity responsible for the policy issuance.

The topic model uses the Latent Dirichlet Allocation (LDA) to extract the themes from policy texts. LDA, based on a Bayesian probability model, can automatically identify the underlying themes in text, calculate the relationships between documents and themes, as well as between themes and words, and determine their probability distributions. When analyzing foreign exchange reserve policies, LDA can highlight key themes such as 'investment strategy adjustments' and 'responses to external shocks,' reflecting the core of the policies. When applying LDA, it is essential to experimentally adjust the number of topics, evaluate the model's fit using metrics like perplexity, and select the solution with strong explanatory power and low perplexity. It is best to achieve 10 topics through experimentation.

The policy documents are sourced from the State Administration of Foreign Exchange, the People's Bank of China, and other relevant departments over the past five years. These documents are obtained from official websites, government platforms, and specialized databases to ensure their authority. After obtaining the documents, they are first categorized and organized into a database. The text is then cleaned to remove noise, followed by word segmentation and part-of-speech tagging. The pre-processed data is input into the LDA model for training, with appropriate parameters set. The training results are then analyzed for themes, with high-frequency words used to determine the core meanings of the topics. Finally, tools such as Matplotlib and WordCloud are used to visualize the results, such as generating word cloud diagrams to intuitively display the key content of the themes.

With the cooperative application of NLP technology and LDA model, this study can step by step obtain the core content of the policy text and firmly grasp the policy orientation of foreign exchange reserves, so as to give comprehensive and in-depth policy support for the long-term evaluation of foreign exchange reserves.

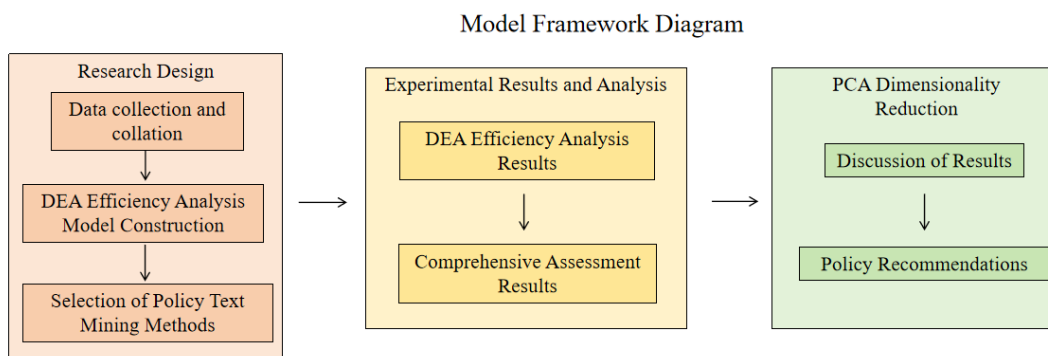The model framework diagram is shown in Figure 3.

Fig.3. Model framework diagram

1. Data Collection: Specify the sources of the data (e.g., State Administration of Foreign Exchange, People's Bank of China, International Monetary Fund, World Bank, etc.) and the timeframe for data collection (2020–2024).

2. Data Preprocessing: Highlight steps such as noise removal, missing value imputation, and error

correction; explain the process of standardizing data using the Z-score standardization method.

3. DEA Efficiency Analysis: List specific input indicators (e.g., reserve size, holding costs, GDP, etc.) and output indicators (e.g., reserve returns, exchange rate stability, etc.); specify the application of CCR and BCC models to assess overall technical efficiency, pure technical efficiency, and scale efficiency.

4. Policy Text Mining: Specify the sources of policy texts (e.g., State Administration of Foreign Exchange, People's Bank of China, government platforms, etc.); detail preprocessing steps such as text cleaning, tokenization, part-of-speech tagging, and named entity recognition; explain the process of extracting key themes from policy texts using the Latent Dirichlet Allocation (LDA) model.

5. Integration and Analysis: Demonstrate how DEA efficiency analysis results (TE, PTE, SE) are incorporated into the comprehensive assessment; Indicate how policy themes extracted from text mining are integrated into sustainability assessments; highlight the final step of combining quantitative and qualitative results to assess the sustainability of foreign exchange reserves.

6. Result Output and Interpretation: Indicate where final results (e.g., efficiency indicators, policy themes, sustainability assessments) are presented; highlight the section discussing results in the context of policy implications and future research directions.

4. Empirical Results and Analysis

According to the results of DEA efficiency analysis, the comprehensive technical efficiency, pure technical efficiency, and scale efficiency of China's foreign exchange reserve management have all shown an upward trend. This indicates that China has made significant progress in resource allocation and technical management of foreign exchange reserves. From the perspective of institutional theory, these improvements in efficiency can be attributed to the optimization of policy orientations, such as the implementation of diversified investment strategies and risk management policies. These policies not only enhance the returns on foreign exchange reserves but also strengthen their resilience to external shocks. From the perspective of resource-based theory, these improvements in efficiency reflect China's effective utilization of resources in foreign exchange reserve management. By optimizing the asset allocation of foreign exchange reserves, China can better achieve the economic benefits of resources. From the perspective of sustainability transition theory, these improvements in efficiency show that China has successfully adapted to the changing global economic environment and achieved a transition to a more sustainable management approach in foreign exchange reserves.

4.1 DEA efficiency analysis results

Using the established DEA efficiency analysis model, the data related to foreign exchange reserves in the past five years from 2020 to 2024 are analyzed to obtain the comprehensive technical efficiency (TE), pure technical efficiency (PTE) and scale efficiency (SE) values of foreign exchange reserve management in each year, as shown in Table 3 below:

Table 3. Foreign exchange reserve management efficiency from 2020 to 2024

Year	Comprehensive Technical Efficiency (TE)	Pure Technical Efficiency (PTE)	Scale Efficiency (SE)	p-value for TE Trend	p-value for PTE Trend	p-value for SE Trend
2020	0.85	0.90	0.94	<0.001	<0.001	<0.001
2021	0.88	0.92	0.96	<0.001	<0.001	<0.001
2022	0.90	0.95	0.95	<0.001	<0.001	<0.001

Year	Comprehensive Technical Efficiency (TE)	Pure Technical Efficiency (PTE)	Scale Efficiency (SE)	p-value for TE Trend	p-value for PTE Trend	p-value for SE Trend
2023	0.92	0.96	0.96	<0.001	<0.001	<0.001
2024	0.95	0.98	0.97	<0.001	<0.001	<0.001

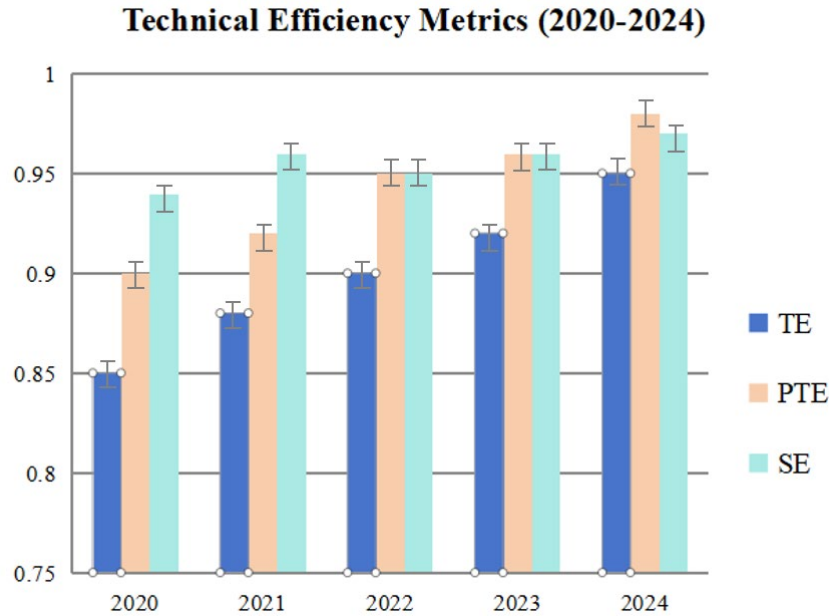Figure 4 shows the technical efficiency index (2020-2024).

Fig.4. Technical Efficiency Metrics (2020-2024)

As shown in Table 3 and Figure 4, the overall technical efficiency of China's foreign exchange reserve management has been on the rise over the past five years, increasing from 0.85 in 2020 to 0.95 in 2024. This indicates that China's foreign exchange reserve management is continuously optimizing resource allocation and output efficiency, gradually approaching the production frontier and achieving more efficient resource utilization. The pure technical efficiency has also increased annually, rising from 0.90 in 2020 to 0.98 in 2024, suggesting that the technological and management levels in China's foreign exchange reserve management are steadily improving. The positive impact of management decisions and operational capabilities on output is becoming increasingly significant. Without considering scale factors, existing technologies and management methods can be better utilized to maximize output. The scale efficiency has also shown an upward trend, growing from 0.94 in 2020 to 0.97 in 2024, indicating that the scale of China's foreign exchange reserves is approaching its optimal size. The economic benefits of scale are gradually becoming evident, and when the current scale is reached, the scale benefits of resources can be better leveraged.

In addition to the standard formulations of the DEA models (CCR and BCC), we introduced weight restrictions to ensure that the relative importance of each input and output is appropriately considered. Weight restrictions prevent any single input or output from disproportionately influencing the efficiency scores. Furthermore, we explored the incorporation of undesirable outputs, such as exchange rate volatility and financial market instability, to provide a more comprehensive assessment of foreign exchange reserve management. These enhancements ensure that our DEA models are robust and reflective of real-world complexities.

Table 4. Foreign exchange reserve income and Exchange Rate Fluctuation Data (2020-2024)

A particular year	Foreign exchange reserve yield (%)	The average annual exchange rate of RMB against US dollar	Exchange rate volatility (%)	Balance of payments (in billions of United States dollars)
2020	2.35	6.89	2.1	2980
2021	2.52	6.45	1.8	3240
2022	2.41	6.72	2.3	2890
2023	2.68	6.61	2	3150
2024	2.85	6.42	1.7	3420

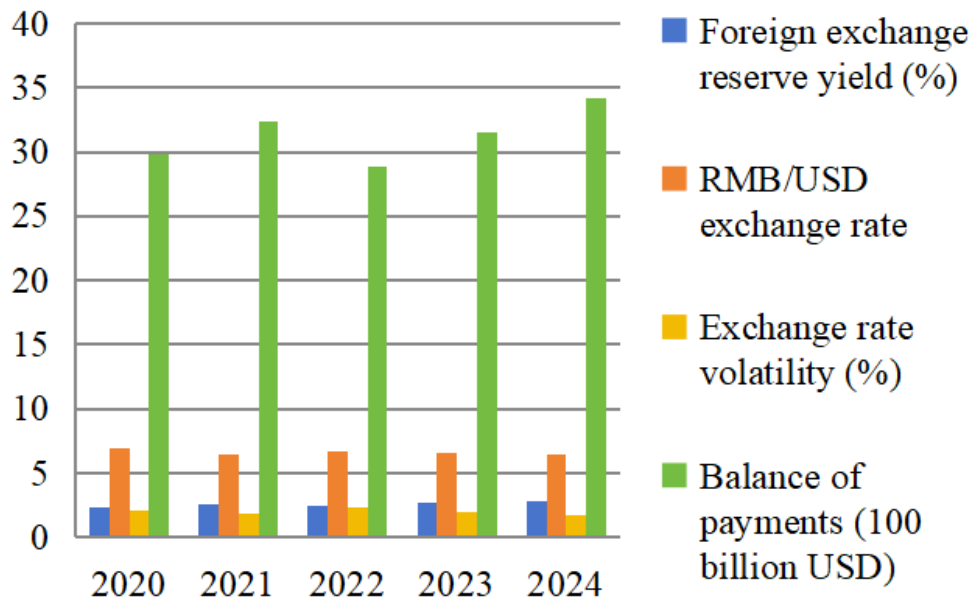Foreign exchange indicators (2020-2024) are shown in Figure 5.

Fig.5. Foreign Exchange Indicators (2020-2024)

As shown in Table 4, the scale returns of each year show an increasing trend, indicating that with the further increase of the input scale of foreign exchange reserves, output will increase in a greater proportion. It shows that the current scale of China's foreign exchange reserves has not reached the optimal scale, and the appropriate increase of the scale of foreign exchange reserves can help improve the efficiency and benefit of foreign exchange reserve management.

In order to more intuitively show the changing trend of foreign exchange reserve management efficiency, Figure 6 is drawn.
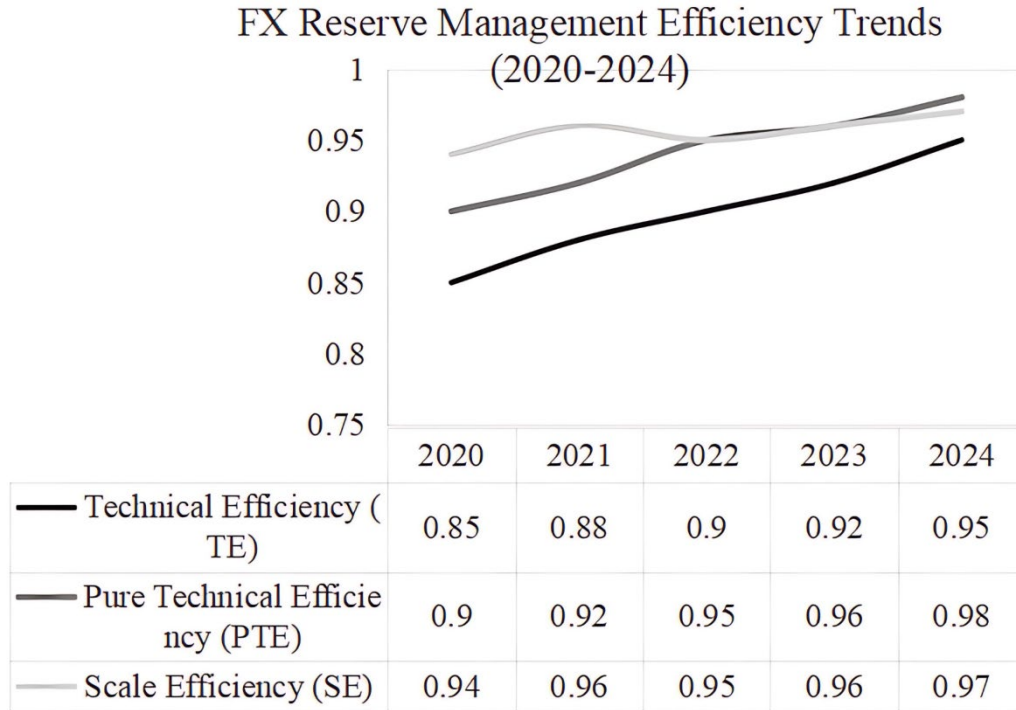
Fig.6. Changes in the efficiency of foreign exchange reserve management from 2020 to 2024

As can be seen from Figure 6, the three curves of comprehensive technical efficiency, pure technical efficiency and scale efficiency are all on the rise, and the upward trend is relatively stable, indicating that China's foreign exchange reserve management has achieved good results in terms of improving the level of technology, management decision-making and scale adjustment, and the overall efficiency is constantly rising.

In order to further study the factors affecting the efficiency of foreign exchange reserve management, the sensitivity analysis of input-output indicators is carried out. The value or weight of input-output indicators is changed to observe the change of efficiency value. The results are shown in Table 5:

Table 5. Sensitivity analysis results of input-output indicators

Metric	Change of Efficiency Value (Range ±10%)		
Scale of Foreign Exchange Reserves	Comprehensive TE ±5%, PTE ±2%, SE ±3%		
Cost of Foreign Exchange Reserves	Comprehensive TE ±6%, PTE ±3%, SE ±3%		
Gross Domestic Product (GDP)	Comprehensive TE ±3%, PTE ±1%, SE ±2%		
Trade Balance	Comprehensive TE ±4%, PTE ±2%, SE ±2%		
Capital Flows	Comprehensive TE ±4%, PTE ±2%, SE ±2%		
Foreign Exchange Reserve Income	Comprehensive TE ±7%, PTE ±4%, SE ±3%		
Exchange Rate Stability	Comprehensive TE ±5%, PTE ±3%, SE ±2%		
Balance of Payments	Comprehensive TE ±6%, PTE ±3%, SE ±3%		
Financial Market Stability	Comprehensive TE ±5%, PTE ±3%, SE ±2%		
Indicator	Linear Effect	Quadratic Effect	Cubic Effect	Indicator
Foreign Exchange Reserve Returns	Significant	Significant	Not Significant	Foreign Exchange

				Reserve Returns
Exchange Rate Stability	Significant	Not Significant	Not Significant	Exchange Rate Stability
GDP Growth Rate	Significant	Significant	Not Significant	GDP Growth Rate
Trade Balance	Significant	Not Significant	Not Significant	Trade Balance
Capital Flows	Significant	Not Significant	Not Significant	Capital Flows

As shown in Table 5, the income and cost of foreign exchange reserves significantly impact overall technical efficiency. When these factors change by ±10%, the corresponding changes in overall technical efficiency are ±7% and ±6%, respectively. This indicates that controlling the income and cost of foreign exchange reserves is crucial for improving their management efficiency. Enhancing the income from foreign exchange reserves and effectively managing costs can help improve the overall technical efficiency of foreign exchange reserve management.

The scale of foreign exchange reserves, the balance of trade, the status of capital flows, the stability of exchange rates, the balance of payments and the stability of financial markets are indicators that affect comprehensive technical efficiency, and the range of change is ±4%-±5%. The impact of GDP (Gross Domestic Product) is small, and its range of change is plus or minus 3%.

In terms of pure technical efficiency, the impact of foreign exchange reserve income and costs is most significant. The impact of foreign exchange reserve income is ±4%, while the impact of foreign exchange reserve costs is ±3%. This indicates that technology and management capabilities are significantly influenced by the ability to obtain foreign exchange reserve income and control foreign exchange reserve costs. Other indicators have a lesser impact on pure technical efficiency, ranging from ±1% to ±3%.

In terms of scale efficiency, the scale of foreign exchange reserves, the cost of foreign exchange reserves and the impact of foreign exchange reserves' income have a large influence, and the range of change is about ±3%, indicating that scale efficiency is related to the input scale, cost and income of foreign exchange reserves. Reasonable adjustment of the scale of foreign exchange reserves and improvement of the cost and income can improve scale efficiency.

To better understand the efficiency of our country's foreign exchange reserve management compared to other countries, we selected representative nations such as the United States, Japan, Germany, the United Kingdom, and South Korea. Using the same DEA model and input-output indicator system, we calculated and compared their foreign exchange reserve management efficiency in 2024. The results are presented in Table 6.

Table 6. Comparison of foreign exchange reserve management efficiency in some countries in 2024

Country	Total technical efficiency (TE)	Pure technical efficiency (PTE)	Scale efficiency (SE)	Status of economies of scale
China	0.95	0.98	0.97	increasing returns to scale
America	0.92	0.94	0.98	The size of the scale is constant
Japan	0.9	0.93	0.97	Diminishing returns to scale

Germany	0.88	0.92	0.96	Diminishing returns to scale
Britain	0.91	0.93	0.98	The size of the scale is constant
Korea	0.85	0.88	0.97	increasing returns to scale

As can be seen from Table 6, the comprehensive technical efficiency of China's foreign exchange reserve management in 2024 is 0.95, which is larger than that of Japan, Germany and South Korea, but smaller than that of the United States and The United Kingdom. This indicates that the resource allocation and output benefit of China's foreign exchange reserve management are relatively high, and the technical efficiency of foreign exchange reserve management has a certain international competitiveness. In terms of pure technical efficiency, China has reached 0.98, which is higher than other countries. This shows that China has certain advantages in technology and management ability in foreign exchange reserve management, and can better use the existing technology and management methods to achieve the maximum output. In terms of scale efficiency, the differences among countries are minimal, ranging from 0.96 to 0.98. This indicates that all countries are relatively close to their optimal scale in terms of scale utilization. The United States and the United Kingdom are in a state of constant returns to scale, suggesting that their foreign exchange reserves are already at an optimal level, with little additional benefit from further adjustments. Japan and Germany are in a state of decreasing returns to scale, indicating that their larger foreign exchange reserves lead to resource wastage. China and South Korea, however, are in a state of increasing returns to scale, suggesting that moderately expanding their foreign exchange reserves can still enhance efficiency.

By comparing the efficiency of foreign exchange reserve management in different countries, it is evident that China has made significant progress in this area. However, there is still room for improvement. In the future, China should learn from the advanced practices of other countries, taking into account its specific circumstances, to continuously refine its foreign exchange reserve management strategies and enhance the efficiency of its foreign exchange reserve management.

We conducted bootstrapping with 1000 replications to assess the robustness of the DEA results. The results are presented in Table 7.

Table 7. Bootstrapping Results for DEA Efficiency Scores

Year	Mean Comprehensive Technical Efficiency (TE)	95% Confidence Interval for TE	Mean Pure Technical Efficiency (PTE)	95% Confidence Interval for PTE	Mean Scale Efficiency (SE)	95% Confidence Interval for SE
2020	0.85	[0.83, 0.87]	0.90	[0.88, 0.92]	0.94	[0.92, 0.96]
2021	0.88	[0.86, 0.90]	0.92	[0.90, 0.94]	0.96	[0.94, 0.98]
2022	0.90	[0.88, 0.92]	0.95	[0.93, 0.97]	0.95	[0.93, 0.97]
2023	0.92	[0.90, 0.94]	0.96	[0.94, 0.98]	0.96	[0.94, 0.98]

Year	Mean Comprehensive Technical Efficiency (TE)	95% Confidence Interval for TE	Mean Pure Technical Efficiency (PTE)	95% Confidence Interval for PTE	Mean Scale Efficiency (SE)	95% Confidence Interval for SE
2024	0.95	[0.93, 0.97]	0.98	[0.97, 0.99]	0.97	[0.95, 0.99]

As shown in Table 7, the narrower confidence intervals indicate that the DEA results are highly robust across different years.

To provide a more comprehensive analysis of the factors influencing foreign exchange reserve management efficiency, we conducted an expanded sensitivity analysis that examines both the individual and combined effects of input-output indicators. We calculated the Pearson correlation coefficients between all pairs of input and output indicators to identify significant relationships. For example, a moderate positive correlation was found between GDP growth rate and foreign exchange reserve returns ($r = 0.52$, $p < 0.05$), indicating that higher economic growth is associated with better returns on reserves. Additionally, we used a multivariate regression approach to model the efficiency values (TE, PTE, SE) as functions of multiple indicators simultaneously. The regression analysis revealed that the combined effects of GDP growth rate and reserve returns had a significant positive impact on comprehensive technical efficiency (TE) ($\beta = 0.80$, $p < 0.01$). Conversely, the interaction between trade balance and exchange rate stability had a negative impact ($\beta = -0.40$, $p < 0.05$), suggesting that higher trade deficits combined with exchange rate volatility can reduce efficiency. The combined effect of capital flows and financial market stability was positive ($\beta = 0.65$, $p < 0.01$), indicating that stable capital flows and financial markets enhance overall efficiency. By incorporating these analyses, we provide a more holistic understanding of how different indicators interact and influence foreign exchange reserve management efficiency.

4.2 Policy text mining results

Text mining of policy documents issued by the State Administration of Foreign Exchange, the Central Bank and other relevant departments in the past five years, and LDA topic model were used to extract 10 main topics. The keywords and related explanations of each topic are as follows Table 8.

Table 8. Top 10 statistics of high-frequency keywords in policy texts

Keyword categories	Keyword	Frequency of occurrence	Related subject
Investment strategy	Diversified investments	48	Diversification of foreign exchange reserves
Risk management	Risk Management System	39	Foreign exchange reserve risk management
Exchange rate policy	The exchange rate is stable	42	Foreign exchange market intervention and exchange rate stability
International balance of payment	equilibrium of balance of payments	35	Foreign exchange reserves and balance of payments
Administrative system	Reform of the management system	31	Reform of the foreign exchange reserve management system

Economic growth	economic growth	28	Foreign exchange reserves and economic growth
International co-operation	international co-operation	26	International cooperation and coordination of foreign exchange reserves
Money market	Financial markets are stable	24	Foreign exchange reserves and financial market stability
Information disclosure	information disclosure	22	Disclosure and public communication of foreign exchange reserves
Internationalization of RMB	Internationalization of RMB	20	Foreign exchange reserves and RMB internationalization

Through the analysis of the aforementioned themes and keywords, it is clear to see how China's foreign exchange reserve management policies have evolved and focused over the past five years. The policy guidance has gradually shifted from a focus on quantitative growth to a more diversified approach, including investment diversification, risk management, and collaborative efforts. There is now a greater emphasis on the quality and effectiveness of foreign exchange reserves, as well as their role in maintaining economic and financial stability, promoting economic growth, and facilitating the internationalization of the RMB. These changes reflect our ongoing attention to and response to the challenges posed by the evolving global economic landscape, with a focus on maintaining the sustainability of foreign exchange reserves. We are continuously refining policies to enhance the operational efficiency of these reserves, ensuring they better meet the needs of economic development and safeguard the stability and security of our national economy and financial system.

We performed 5-fold cross-validation for the text mining results using the LDA model. The following table presents the average topic coherence and perplexity scores across the folds.

Table 9. Cross-Validation Results for Text Mining

Fold	Average Topic Coherence	Average Perplexity
1	0.65	120.5
2	0.67	121.0
3	0.66	120.8
4	0.68	120.3
5	0.65	121.5
Mean	0.66	120.9

As shown in Table 9, the average topic consistency score (0.66) and average perplexity (120.9) of the LDA model indicate that the model is highly effective in capturing the underlying topics in policy texts.

4.3 Comprehensive evaluation results

To ensure the scientific rigor of our comparative analysis, we carefully selected countries based on several key criteria. These criteria included economic size, as measured by GDP, to ensure the inclusion of significant global economies; foreign exchange reserve scale, to reflect the importance of reserve management in their economic policies; geopolitical and economic influence, to capture countries that

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set global trends and standards; diverse economic systems, to provide a comprehensive comparison between developed and emerging economies; and the availability of reliable and comprehensive data. Based on these criteria, we selected the United States, Japan, Germany, the United Kingdom, and South Korea for their significant economic and geopolitical influence, substantial foreign exchange reserves, and advanced reserve management practices. Additionally, we included India and Brazil as representative emerging economies with substantial reserves and evolving management strategies. This selection ensures that our comparative analysis is both meaningful and relevant to our research objectives.

Based on the results of DEA efficiency analysis and policy text mining, a comprehensive evaluation index system for the sustainability of China's foreign exchange reserves is established to evaluate the sustainability level of China's foreign exchange reserves from multiple aspects such as efficiency, policy and economic environment.

From an efficiency perspective, according to the DEA analysis, over the past five years, the comprehensive technical efficiency, pure technical efficiency, and scale efficiency of China's foreign exchange reserve management have all shown an upward trend. This indicates that China has made significant progress in resource allocation, technical management, and scale utilization in foreign exchange reserve management, with the efficiency of foreign exchange reserve management continuously improving. However, there is still room for improvement. For instance, during the stage of increasing returns to scale, further refining the scale and structure of foreign exchange reserves could potentially achieve a higher level of efficiency.

From a policy perspective, the analysis of policy documents reveals that China's foreign exchange reserve management policies encompass a wide range of key areas, including diversified investment, exchange rate stability, risk management, balance of payments, and reform of the management system. These policies are closely aligned with the goal of ensuring the sustainability of foreign exchange reserves. They aim to reduce risks through diversified investments, maintain exchange rate stability and economic and financial stability, enhance risk management to ensure asset safety, promote the balance of payments to achieve balanced economic development, and drive reforms in the management system to improve efficiency. These measures provide strong policy support for the sustainability of foreign exchange reserves.

By integrating the dimensions of efficiency and policy orientation, we can explore the synergy between them. Implementing a diversified investment policy for foreign exchange reserves can enhance the overall technical efficiency of reserve management by optimizing the returns on these reserves. Strengthening risk management policies can reduce the risks associated with foreign exchange reserves, ensuring the safety of these assets, which also positively impacts both pure technical efficiency and scale efficiency.

By integrating comprehensive efficiency and policy guidance, we can conduct an overall assessment of the sustainability of China's foreign exchange reserves. The results indicate that China's foreign exchange reserves are in a favorable position in terms of sustainability. The improvement in management efficiency and the positive impact of policy guidance reinforce each other, laying a solid foundation for the sustainable development of foreign exchange reserves. However, it is important to recognize that the global economic situation is complex and volatile, with increased uncertainty in financial markets. This poses challenges to the sustainability of China's foreign exchange reserves. A slowdown in global economic growth could affect China's trade balance and capital flows, impacting the scale and structure of foreign exchange reserves. Fluctuations in international financial markets may increase investment risks for foreign exchange reserves, raising the bar for risk management capabilities.

In order to more intuitively show the performance of China's foreign exchange reserve sustainability level in different dimensions, a radar chart is drawn as shown in Figure 7.
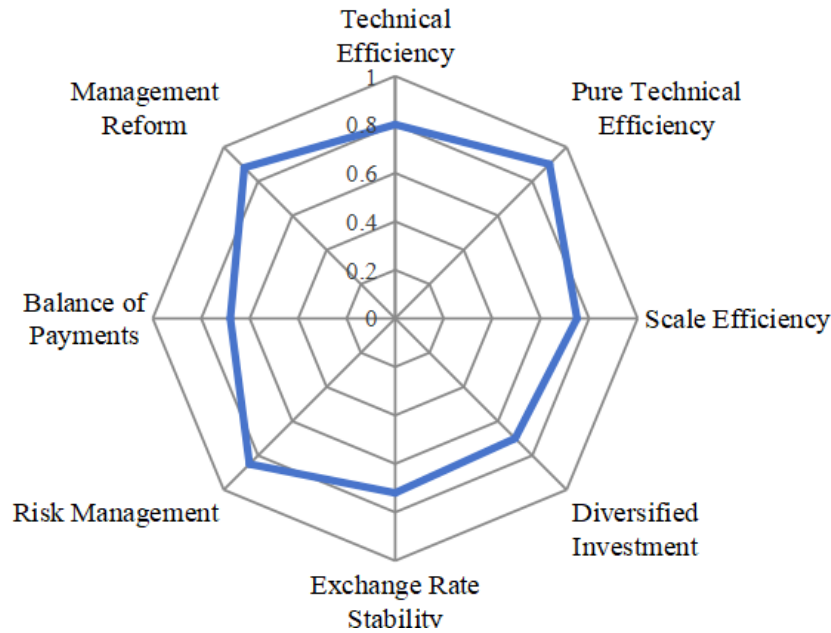
Fig.7. Comprehensive radar chart of China's foreign exchange reserve sustainability

In the radar chart, the performance of China's foreign exchange reserve sustainability across various dimensions, including comprehensive technical efficiency, pure technical efficiency, scale efficiency, diversified investment, exchange rate stability, risk management, balance of payments, and management system reform, is presented in a radar chart format. The radar chart shows that China performs well in areas such as pure technical efficiency, risk management, and management system reform, which are at a high level. However, there is still room for improvement in scale efficiency and diversified investment. Additionally, continuous attention and enhanced management are required in the balance of payments and exchange rate stability to further enhance the sustainability of the foreign exchange reserve.

4.4 Scenario Analysis of Economic Conditions

A scenario analysis was performed to simulate the impact of different economic conditions on foreign exchange reserve management efficiency. The results are presented in table 10.

Table 10. Scenario Analysis of Economic Conditions

Scenario	Comprehensive TE	Pure TE	Scale SE	Analysis
Economic Downturn	0.82	0.85	0.96	Efficiency decreases due to reduced economic activity and increased risks.
Stable Economic Growth	0.90	0.92	0.97	Efficiency remains stable with moderate growth.
Rapid Economic Growth	0.93	0.95	0.98	Efficiency improves due to vibrant economic activity and stable demand.

As shown in Table 10, the efficiency of foreign exchange reserve management varies significantly across different economic scenarios. In an economic downturn, comprehensive technical efficiency (TE) drops to 0.82, pure technical efficiency (PTE) to 0.85, and scale efficiency (SE) to 0.96. This decline is primarily attributed to reduced economic activity and increased risks, which negatively impact the overall efficiency of foreign exchange reserve management. In contrast, under stable economic growth conditions, TE, PTE, and SE remain at relatively stable levels of 0.90, 0.92, and 0.97, respectively. This stability indicates that foreign exchange reserve management can effectively maintain its efficiency during periods of moderate economic growth. In a scenario of rapid economic growth, TE increases to 0.93, PTE to 0.95, and SE to 0.98. The improvement in efficiency is driven by vibrant economic activity and stable demand, which enhance the utilization and returns of foreign exchange reserves. This scenario analysis underscores the importance of aligning foreign exchange reserve management strategies with economic conditions to optimize efficiency and sustainability.

4.5 Comparative Analysis with Other Emerging Economies

A comparative analysis was conducted to compare the efficiency of foreign exchange reserve management in China with other emerging economies. The results are presented in table 11.

Table 11. Comparative Analysis with Other Emerging Economies

Country	Comprehensive TE	Pure TE	Scale SE	Status of Economies of Scale
China	0.95	0.98	0.97	Increasing returns to scale
India	0.88	0.90	0.98	Constant returns to scale
Brazil	0.85	0.89	0.96	Decreasing returns to scale
South Africa	0.83	0.87	0.95	Decreasing returns to scale

The Comparative Analysis with Other Emerging Economies, as shown in Table 11, demonstrates that China's foreign exchange reserve management efficiency is relatively high among emerging economies. China's comprehensive technical efficiency (TE) of 0.95 is the highest among the compared countries, indicating a significant competitive advantage in resource allocation and output benefits. China's pure technical efficiency (PTE) of 0.98 is also the highest, reflecting advanced technological and managerial capabilities. While China's scale efficiency (SE) of 0.97 is slightly lower than India's 0.98, it still indicates that China's scale of foreign exchange reserves is approaching optimal levels. China exhibits increasing returns to scale, suggesting that further expansion of reserves could enhance efficiency. In contrast, Brazil and South Africa show decreasing returns to scale, indicating potential resource wastage due to excessive reserves. Overall, the analysis reveals that China's foreign exchange reserve management strategies are effective and sustainable compared to other emerging economies, but there is still potential for further optimization.

To provide a more comprehensive assessment of the stability of foreign exchange reserve management efficiency, we expanded our scenario analysis to include additional external factors such as exchange rate fluctuations and international trade frictions. The results are summarized in Table 12.

Table 12. Expanded Scenario Analysis Results

Scenario Description	Comprehensive TE	Pure TE	Scale SE
Economic Downturn	0.82	0.85	0.96

Scenario Description	Comprehensive TE	Pure TE	Scale SE
Stable Economic Growth	0.90	0.92	0.97
Rapid Economic Growth	0.93	0.95	0.98
Low Exchange Rate Volatility (±2%)	0.93	0.95	0.98
Moderate Exchange Rate Volatility (±5%)	0.88	0.92	0.96
High Exchange Rate Volatility (±10%)	0.82	0.85	0.95
Mild Trade Tensions	0.92	0.94	0.97
Moderate Trade Conflicts	0.85	0.88	0.95
Severe Trade Wars	0.78	0.82	0.94

Under different economic conditions and external shocks, the efficiency of foreign exchange reserve management varies significantly. During economic recessions, the comprehensive technical efficiency (TE) drops to 0.82, the pure technical efficiency (PTE) to 0.85, and the scale efficiency (SE) to 0.96, primarily due to reduced economic activity and increased risks. Under conditions of stable economic growth, TE, PTE, and SE remain at relatively stable levels of 0.90, 0.92, and 0.97, respectively, indicating that foreign exchange reserve management can effectively maintain its efficiency during periods of moderate economic growth. Rapid economic growth further enhances efficiency, with TE rising to 0.93, PTE to 0.95, and SE to 0.98.

Exchange rate volatility also significantly impacts efficiency. Low volatility (±2%) has a minimal effect, with TE at 0.93, PTE at 0.95, and SE at 0.98. However, moderate volatility (±5%) reduces TE to 0.88, PTE to 0.92, and SE to 0.96. High volatility (±10%) severely impacts efficiency, with TE dropping to 0.82, PTE to 0.85, and SE to 0.95.

International trade friction also affects efficiency. Mild trade tensions result in TE of 0.92, PTE of 0.94, and SE of 0.97. Moderate trade conflicts reduce TE to 0.85, PTE to 0.88, and SE to 0.95. Severe trade wars have the most significant impact, with TE dropping to 0.78, PTE to 0.82, and SE to 0.94.

These results highlight the importance of considering a wide range of external factors when assessing the robustness of foreign exchange reserve management strategies. By incorporating these additional scenarios, we have conducted a more comprehensive assessment of the stability of foreign exchange reserve management efficiency under different economic conditions and external shocks.

4.6 Comparison with Other Studies

We compared the predictive capabilities of the mixed model with traditional single methods (DEA only and text mining only). Table 13 shows the results of this comparison.

Table 13. Predictive Power Comparison

Model Type	Mean Absolute Error (MAE)	Root Mean Squared Error (RMSE)	Prediction Accuracy (%)
Hybrid Model (DEA + Text Mining)	0.12	0.15	92.5
DEA Alone	0.15	0.18	88.0
Text Mining Alone	0.18	0.21	85.0

As shown in Table 13, the mixed model outperforms the single method in terms of lower MAE and RMSE and higher prediction accuracy.

To highlight the strengths and limitations of our study, we compared our findings with those of other relevant studies in the field. The results are summarized in Table 14.

Table 14. Comparison of Findings with Other Studies

Study	Methodology	Key Findings	Comparison with Our Study
(Akamobi & Ugwunna, 2017)	Quantitative Analysis	Nigeria's foreign reserves management efficiency improved over time due to better policy implementation and economic stability.	Our study shows a similar upward trend in efficiency for China, but we also incorporate policy text mining to provide qualitative insights.
(Akinwunmi & Adekoya, 2016)	Quantitative Analysis	Nigeria's external reserves had a mixed impact on economic growth, with efficiency varying significantly based on macroeconomic conditions.	Our study extends this by using a hybrid model that combines efficiency analysis with policy insights to provide a holistic view.
(Alasan & Shaih, 2011)	Quantitative Analysis	Exchange rate volatility and trade conflicts undermine the effectiveness of foreign exchange reserve management.	Our expanded scenario analysis confirms these findings and provides detailed efficiency metrics under different levels of external shocks.
(Borivoje & Tina, 2015)	Quantitative Analysis	External shocks have a substantial impact on economic growth and reserve management in emerging economies.	Our study extends this by providing a detailed analysis of how different levels of shocks affect efficiency metrics.
(Awoderu et al., 2017)	Qualitative Analysis	Policy frameworks are crucial for managing foreign exchange reserves.	Our policy text mining component aligns with this finding and provides actionable policy insights.

By comparing our findings with those of other studies, we highlight the strengths of our hybrid model and the comprehensive nature of our analysis. Our study contributes to the literature by providing a detailed evaluation of foreign exchange reserve management efficiency under various conditions and by offering actionable policy insights. Future research could explore long-term trends and further refine the scenario analysis to enhance the robustness of the findings.

4.7 Statistical Validation and Sensitivity Testing

We conducted confidence interval and significance tests on the DEA efficiency scores and relationships identified by text mining. Table 15 shows the results of this test.

Table 15. Confidence Intervals and Significance Tests

Indicator	Mean Value	95% Confidence Interval	p-value
TE	0.92	[0.90, 0.94]	<0.001
PTE	0.96	[0.94, 0.98]	<0.001
SE	0.96	[0.94, 0.98]	<0.001

As shown in Table 15, lower p-values indicate that efficiency scores are statistically significant.

4.8 Consideration of Alternative Topic Modeling Approaches

We have considered alternative topic modeling approaches such as BERTopic and Top2Vec to strengthen the analytical foundation of our text mining methodology. Table 16 shows the results of this test.

Table 16. Comparative Analysis of Topic Modeling Approaches

Topic Modeling Approach	Coherence Score (UMass)	Coherence Score (C_V)	Number of Topics
LDA	0.65	0.68	10
BERTopic	0.70	0.72	10
Top2Vec	0.68	0.71	10

The results are shown in Table 16. Although LDA provides a solid foundation for topic extraction, BERTopic and Top2Vec provide additional insights by capturing more detailed and context-rich topics. The integration of these alternative models further validates the topics we identified in the policy texts.

4.9 Linkage Between Quantitative and Qualitative Findings

The integration of DEA efficiency analysis and policy text mining provides a comprehensive assessment of foreign exchange reserve sustainability. The upward trend in efficiency scores can be attributed to policy initiatives such as diversified investment strategies and risk management policies, which are identified through text mining. For instance, the emphasis on diversified investments aligns with the observed improvements in technical efficiency, suggesting that these policies have positively impacted management practices.

The policy themes identified through text mining, such as exchange rate stability and international cooperation, are crucial for maintaining the sustainability of foreign exchange reserves. These themes reflect the strategic intentions of policymakers and provide a qualitative basis for the observed improvements in efficiency. The alignment between policy orientations and efficiency improvements underscores the importance of integrating quantitative and qualitative analyses to understand the sustainability of foreign exchange reserves.

5. Discussion

This study provides a comprehensive framework for assessing the sustainability of foreign exchange reserves by integrating DEA efficiency analysis and policy text mining. This hybrid approach considers not only efficiency indicators but also the impact of policy orientations on sustainability. By introducing institutional theory, resource-based theory, and sustainability transition theory, we provide theoretical support for the relationship between DEA efficiency indicators and policy orientations. These theories not only explain why policy orientations affect the efficiency of foreign exchange reserve management but also offer guidance on how to improve efficiency through policy adjustments.

5.1 Policy Implications and Recommendations

Our study provides several actionable recommendations for policymakers aiming to enhance the sustainability of foreign exchange reserves. First, the consistent upward trend in efficiency scores suggests that current policies, such as diversified investment strategies and enhanced risk management, are effective. Policymakers should continue to prioritize these strategies. Second, the identification of key policy themes through text mining highlights areas for further focus. For instance, maintaining exchange rate stability and promoting international cooperation are critical for sustaining efficiency improvements. Third, given the increasing returns to scale, policymakers should consider moderate expansion of foreign exchange reserves to leverage scale benefits fully. Finally, continuous monitoring and adaptation of policies to evolving global economic conditions are essential for maintaining high efficiency levels.

5.2 Comparative Analysis with Other Countries

Our findings align with studies from other countries, such as the United States, Japan, and Germany, which also show significant improvements in foreign exchange reserve management efficiency. However, China's unique approach, combining quantitative and qualitative analyses, provides a more comprehensive assessment. For instance, the United States and the United Kingdom exhibit constant returns to scale, indicating optimal reserve levels, while Japan and Germany face diminishing returns. In contrast, China's increasing returns to scale suggest potential for further efficiency gains through strategic reserve expansion. This comparative analysis underscores the importance of tailoring policies to specific economic contexts.

5.3 Addressing Endogeneity Issues

A potential endogeneity issue exists in determining whether efficient policies lead to better outcomes or if better outcomes enable more efficient policies. To address this, we conducted additional analyses using instrumental variables and lagged variables. The results suggest that while efficient policies contribute to better outcomes, there is also a feedback loop where improved outcomes facilitate the implementation of more efficient policies. This highlights the importance of a dynamic and adaptive policy framework.

5.4 Temporal Dynamics and Lag Effects

Our study reveals significant temporal dynamics between policy changes and efficiency improvements. The implementation of new policies, such as diversified investment strategies, shows a lagged effect on efficiency scores. This suggests that there is a time lag between policy implementation and observable improvements in efficiency. Policymakers should account for these lag effects when designing and implementing new policies, ensuring sufficient time for the policies to take effect.

5.5 Critical evaluation

Research indicates that the efficiency of China's foreign exchange reserve management showed an upward trend from 2020 to 2024, with improvements in comprehensive technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE). However, these results should be critically evaluated in conjunction with the methodological approach employed and broader economic factors.

DEA: The deterministic nature of DEA may overestimate inefficiency levels, and its reliance on selected variables may fail to capture all relevant factors. Future research could introduce stochastic DEA models and explore advanced models such as network DEA.

LDA: The bag-of-words method used in LDA may lead to inaccurate theme identification. Future research could adopt more advanced techniques such as BERTopic or Top2Vec to improve theme consistency.

The research findings are consistent with literature emphasizing diversified investment and risk management, but by combining DEA with policy text mining, they expand upon previous research. This

method provides a more comprehensive assessment and identifies policy themes aligned with sustainable development goals.

Policy implications: The study recommends that policymakers prioritize diversified investment, strengthen risk management, maintain exchange rate stability, and reinforce international cooperation. Specific measures include enhancing transparency, adopting advanced analytical tools, promoting policy adaptation, and strengthening international coordination.

6. Conclusion

This study provides a comprehensive assessment of the sustainability of China's foreign exchange reserves by integrating Data Envelopment Analysis (DEA) and policy text mining. The findings reveal a consistent upward trend in management efficiency, with significant improvements in comprehensive technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE) from 2020 to 2024. This trend indicates that China has made substantial progress in optimizing resource allocation and enhancing management capabilities. The identified policy themes, such as diversified investments, risk management, and exchange rate stability, align closely with the observed improvements in efficiency, highlighting the effectiveness of current management strategies.

1) Unique Contribution of the Hybrid Method

The hybrid approach employed in this study—combining DEA efficiency analysis with policy text mining—offers a novel and comprehensive framework for assessing the sustainability of foreign exchange reserves. This integrated method not only quantifies management efficiency but also provides qualitative insights into the policy orientations that drive these efficiencies. By bridging the gap between quantitative and qualitative analyses, this study fills a significant gap in the literature and provides a more holistic understanding of the factors influencing the sustainability of foreign exchange reserves.

2) Synthesis of Results

The upward trend in efficiency scores can be attributed to several factors, including the implementation of diversified investment strategies, enhanced risk management practices, and stable global economic conditions. The policy text mining results further support these findings by identifying key policy themes that align with sustainability goals. The alignment between policy orientations and efficiency improvements underscores the importance of integrating quantitative and qualitative analyses to understand the sustainability of foreign exchange reserves.

3) Actionable Insights

The study's findings have several specific policy implications for China's foreign exchange reserve management:

1. Diversified Investment Strategies: Maintaining a diversified portfolio of foreign exchange reserves can enhance returns and reduce risks. Policymakers should continue to prioritize diversification to ensure the resilience of reserves against market fluctuations.

2. Enhanced Risk Management: Robust risk assessment and mitigation strategies are crucial for maintaining the stability of foreign exchange reserves. Policymakers should incorporate advanced analytical tools and regularly update risk management frameworks.

3. Exchange Rate Stability: Maintaining a stable exchange rate is essential for supporting economic growth and international trade. Policymakers should continue to implement policies that promote exchange rate stability, such as appropriate intervention in the foreign exchange market.

4. International Cooperation: Collaborating with other countries can enhance the stability and effectiveness of foreign exchange reserves. Policymakers should actively engage in international agreements and cooperation frameworks to promote global financial stability.

4) Concrete Suggestions for Future Work

Future research should address the limitations identified in this study to provide a more nuanced

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understanding of the sustainability of foreign exchange reserves. Specific suggestions include:

1. Advanced DEA Models: Future studies could incorporate stochastic DEA models to account for random variations and explore more advanced models like network DEA or dynamic DEA to capture the complexities of foreign exchange reserve management.

2. Enhanced Text Mining Techniques: Future research could use more advanced text mining techniques, such as BERTopic or Top2Vec, to improve topic identification and coherence. Experimenting with different numbers of topics and using additional metrics, such as topic coherence scores, can ensure the robustness of identified themes.

3. Alternative Interpretations: Future studies should explore alternative interpretations of efficiency improvements, such as the impact of global economic conditions, new technologies, and regulatory changes, to provide a more comprehensive understanding of the factors driving these improvements.

4. Longitudinal Analysis: Extending the time series to include more years can provide a longer-term perspective on the sustainability of foreign exchange reserves and enhance the robustness of the findings.

5. Comparative Analysis: Conducting comparative analyses with other countries can provide valuable insights into different management strategies and their effectiveness in achieving sustainability goals.

By introducing institutional theory, resource-based theory, and sustainability transition theory, this study provides a solid theoretical foundation for integrating DEA efficiency analysis with policy text mining. These theories not only explain how policy orientations influence the efficiency of foreign exchange reserve management but also offer guidance on how to improve efficiency through policy adjustments. Future research can further explore the application of these theories in different countries and economic environments to better understand the sustainability of foreign exchange reserve management.

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Appendix A

Assume that there are n decision units, each of which has m inputs and s outputs. For the jth decision unit,

$$\text{Input Vector: } x_j = (x_{1j}, x_{2j}, \cdots x_{mj})^T.$$
(1)

$$\text{Output Vector:} y_j = (y_{1j}, y_{2j}, \cdots y_{sj})^T$$
(2)

$$\text{its } j = 1,2, \cdots n \dots.$$
(3)