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Analysing the financial innovation-based characteristics of stock market efficiency using fuzzy decision-making technique

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Abstract

Necessary actions should be taken to ensure stock market efficiency; thus, financial innovation-based criteria that affect stock market efficiency should be improved. However, simultaneously improving all criteria is difficult; therefore, performing priority analysis is important for carrying out this process effectively and efficiently. Accordingly, this study aims to evaluate the financial innovation-based characteristics of stock market efficiency. This study's main research question within this framework is identifying which factors should be prioritized to improve the stock market. In this scope, we created a novel fuzzy decision-making model consisting of two stages. First, selected criteria for the financial innovation-based characteristics of stock market efficiency are weighted. In this process, quantum spherical fuzzy sets based on DEMATEL are considered. In the second stage, selected economies are ranked using the technique for order of preference by similarity to ideal solution (TOPSIS) approach. This study's main contribution is that the DEMATEL technique in calculating criterion weights in the decision-making analysis process provides some advantages. With the help of this situation, the causal directions between these items can be considered; thus, it is possible to determine the most accurate strategies. The findings demonstrate that providing tax advantages is the most important factor in ensuring stock market efficiency. Moreover, the excellence of the financial system is critical in ensuring stock market efficiency. In this context, it is possible to provide tax advantages, especially for long-term investments. Thus, long-term investments can be increased, significantly increasing the market's stability.

Keywords: Efficiency, Indexes, Stock market, Decision-making, Financial innovation

Introduction

Stock market efficiency shows that prices reflect the available information in the market. The efficiency of these markets is important and necessary in many respects. First, this efficiency makes it possible to ensure effective resource distribution. In other words, this ensures the market's most efficient distribution of capital, which contributes to the effective development of investments (dos Santos Maciel 2023). Conversely, the efficiency of these markets allows stocks to be priced fairly and increases investors' confidence in the market; thus, making investment decisions more safely is possible. Ensuring the

efficiency of stock markets also reduces information asymmetry; therefore, investors can make more accurate investment decisions. Moreover, it is possible to increase the efficiency of capital markets thanks to the efficiency of the markets (Rönkkö et al. 2024), which supports economic growth as it increases investments. Furthermore, efficient markets enable investors to manage their risks better.

Some improvements must be made to ensure stock market efficiency. First, financial instruments in the market must be diversified so investors can manage risk more effectively. Similarly, diversification of investment strategies will be possible in this process (Huang et al. 2024). Technological development is another essential factor in this process. For example, blockchain technology allows commercial activities to be carried out more securely and increases market efficiency. Similarly, comprehensive analyses can be performed with advanced technologies, such as big data analysis and artificial intelligence, which help investors make informed decisions. In contrast, the development of regulation technologies allows legal requirements to be determined for investors' transactions (Bhatia 2023), which contributes significantly to increasing the reliability of the market. Moreover, innovative financing models also help ensure stock market efficiency. For example, more investors can participate in the market with innovative financial products like crowdfunding.

Financial innovation-based criteria that affect stock market efficiency need to be improved; however, it is challenging to improve all criteria simultaneously. Therefore, performing priority analysis is essential for carrying out this process effectively and efficiently. Realizing financial innovations requires significant time, money, and human resources; however, since these resources are limited, it is impossible to innovate much (Yaya et al. 2024). Therefore, the market performance can be increased through the effective use of resources. Conversely, owing to the priority analysis, which factors can have the greatest impact on stock market efficiency can be understood. In this way, focusing primarily on innovations that will provide the highest return is possible. Similarly, this priority analysis allows more effective risk management and strategic planning. If financial innovation-based factors are not determined to ensure stock market efficiency, various problems and inefficiencies may arise. For example, this situation causes both a decrease in liquidity in the market and an increase in transaction costs, significantly reducing investor confidence, as it will increase the risks in the market. Therefore, financial innovations and their proper integration are vital to ensure efficiency in stock markets. As a result, studies are needed to determine the factors that most affect this process; however, few studies focus on this issue in the literature, representing a critical gap in financial innovation research.

Accordingly, this study aims to evaluate the financial innovation-based characteristics of stock market efficiency. In this process, this study's central research question identifies the factors that should be prioritized to improve the stock market. For this purpose, we created a novel fuzzy decision-making model comprising two stages. In the first stage, selected criteria for the financial innovation-based characteristics of stock market efficiency are weighted. In this process, quantum spherical fuzzy sets based on decision-making trial and evaluation laboratory (DEMATEL) are considered. In the second stage, selected economies are ranked using the technique for order of preference by similarity to ideal solution (TOPSIS) approach. The biggest motivation for this study is the need

for a comprehensive analysis in determining financial innovation-based criteria that affect stock market efficiency. This issue requires a detailed analysis because many indicators affect this process; therefore, this study aims to answer these questions by establishing a new multicriteria decision-making model.

This study's main contributions are as follows. (i) Using the DEMATEL technique to calculate criterion weights in the decision-making analysis process provides some advantages to the model. Financial innovation-based criteria that affect stock market efficiency may affect each other; therefore, it is vital to consider this causal relationship when determining the most important criteria. In this way, it is possible to determine the most accurate strategies. The most significant advantage of the DEMATEL technique over similar models is creating an impact relation map during the analysis process. (ii) The use of quantum spherical fuzzy numbers in the proposed model also increases the quality of the model. Finding financial innovation-based criteria that affect stock market efficiency is a very complex process. In other words, this process contains significant uncertainties. To solve this problem, we integrate quantum theory with spherical numbers, which contributes significantly to reducing the uncertainty of the process.

The remainder of this paper is structured as follows. Section "[Literature review](#)" presents the literature evaluation, while Section "[Proposed model](#)" provides the steps of the proposed model. Section "[Analysis results](#)" presents the analysis results, Section "[Discussion](#)" provides the discussion, and Section "[Conclusion](#)" concludes.

Literature review

Different factors affect stock market efficiency. Reasonable transaction costs are of great importance in this process. Low transaction costs encourage investors to make more transactions (Lee et al. 2024), which creates a high transaction volume, increasing liquidity in the market. An important disadvantage of high transaction costs is that they make it difficult for investors to enter the market (Meng et al. 2023). Conversely, lower costs enable a more comprehensive range of investors to participate in the market. Additionally, Bock and Geissel (2024) indicated that reasonable transaction costs help portfolio diversification; thus, effective investment risk management becomes increasingly possible. Moreover, Erer et al. (2023) determined that investors trade more in the market thanks to lower transaction costs. In this way, information flow will occur faster, and this contributes to reducing information asymmetry. Low transaction costs increase investors' confidence in the market, which also enables the market to develop further.

Effective risk management is also essential to ensure stock market efficiency and allow investors to make better decisions (Moudud-Ul-Huq and Rahman 2024). In this way, it is possible to prevent sudden price movements. Reducing volatility makes it easier to prevent potential financial crises (Yang et al. 2024). Effective risk management can also increase investor confidence. In this process, investors can trade more comfortably and safely in the market (Meng et al. 2023), which significantly supports increasing the transaction volume. In contrast, Chang et al. (2023) found that effective risk management reduces manipulations, which helps prevent investors from suffering major losses. Moreover, Xu et al. (2023) discussed that effective risk management helps investors make more informed and strategic decisions; thus, return optimization can be achieved

through more successful portfolio management. Similarly, new financial tools used in risk management can improve the market's efficiency.

Ensuring technological developments is also vital in increasing stock market efficiency. Thanks to technological developments, it is possible to increase processing speeds (Chen and Li 2023), increasing liquidity in the market. Additionally, advanced technologies allow investors to trade quickly and reliably; thus, it is possible to increase the efficiency of the market (Patra and Hiremath 2024; Htun et al. 2023). Moreover, access to information can further increase with technological developments. In this process, Shahvaroughi Farahani and Farrokhi-Asl (2023) found that investors could access information quickly and make faster and more accurate decisions, helping to reduce information asymmetry. This situation allows prices in the market to be determined more accurately. Furthermore, Jagirdar and Gupta (2023) concluded that another advantage of technological development is reducing transaction costs, significantly contributing to more investors trading in the market. Thus, the market's efficiency can be increased by raising the liquidity. Moreover, Shrestha et al. (2023) showed that an important contribution of technological development to this process is increasing investors' confidence in the market. This situation significantly supports the development of these markets.

Tax advantage is another factor to consider in increasing stock market efficiency. The biggest benefit of this issue is reducing transaction costs, which increases investors' profitability; thus, more transactions can be made in the market (Jaquart et al. 2023), and the efficiency of the market will increase. Furthermore, tax incentives enable investors of different profiles and income levels to participate in the market (Gao et al. 2024). Moreover, interest in long-term investments may increase with tax advantages; thus, stock markets can become more efficient (Narayan et al. 2023). The biggest benefit of this situation is the reduction of speculation. Lee and Choi (2023) identified that this significantly reduces market volatility; thus, a more sustainable market can be achieved. Furthermore, Aloosh et al. (2023) demonstrated that tax advantages allow investors to better manage their risks by diversifying their portfolios, enabling more successful investment strategies in the stock market (Adediran et al. 2023). Similarly, tax advantages make domestic markets more attractive to international investors (Saqib et al. 2021; Mikhaylov et al. 2023; Moiseev et al. 2023).

This literature review revealed some vital points. For example, ensuring the efficiency of stock markets is critical for the country's economic development; therefore, necessary actions must be taken to increase the efficiency of this market. In this context, factors such as technological development, cost efficiency, tax advantage, and effective risk management are of paramount importance to the efficiency of this market. Nevertheless, because the resources are limited, it is impossible to make many innovations simultaneously; therefore, it is necessary to find the factors that most affect the efficiency of this market. In this way, it is possible to determine effective investment strategies by focusing on more important indicators; however, few studies examine this issue in the literature, which is the most important research gap. To eliminate this deficiency, we establish a new decision-making model and conduct priority analysis for these variables (Mikhaylov et al. 2023).

Proposed model

The details of the techniques used in the proposed model are explained below.

Quantum spherical fuzzy sets with golden cut

Quantum theory can make successful future estimations; therefore, this theory is considered in the fuzzy decision-making analysis. Uncertainty in the process can be minimized with the help of this integration. Equations (1)–(3) present the details of this situation (Hacioglu et al. 2023).

$$Q(|u \rangle) = \varphi e^{j\theta} \tag{1}$$

$$|\zeta \rangle = \{|u_1 \rangle, |u_2 \rangle, \dots, |u_n \rangle\} \tag{2}$$

$$\sum_{|u\rangle \subseteq |\zeta\rangle} |Q(|u \rangle)| = 1 \tag{3}$$

In this context, ζ defines the set of collective exhaustive events $|u_i \rangle$, φ^2 is the amplitude result, and θ^2 refers to the phase angle. Spherical fuzzy sets (\tilde{A}_S) are created by the extensions of the classical fuzzy numbers. The membership, nonmembership, and hesitancy degrees can be considered due to these sets. Equations (4) and (5) give information about the details of these sets (Yüksel and Dinçer 2023).

$$\tilde{A}_S = \left\{ \langle u, (\mu_{\tilde{A}_S}(u), \nu_{\tilde{A}_S}(u), h_{\tilde{A}_S}(u)) | u \in U \right\} \tag{4}$$

$$0 \leq \mu_{\tilde{A}_S}^2(u) + \nu_{\tilde{A}_S}^2(u) + h_{\tilde{A}_S}^2(u) \leq 1, \forall u \in U \tag{5}$$

Equation (6) demonstrates the integration of quantum theory with spherical fuzzy sets.

$$|\zeta_{\tilde{A}_S} \rangle = \left\{ \langle u, (\varsigma_{\mu_{\tilde{A}_S}}(u), \varsigma_{\nu_{\tilde{A}_S}}(u), \varsigma_{h_{\tilde{A}_S}}(u)) | u \in 2^{|\zeta_{\tilde{A}_S}|} \right\} \tag{6}$$

In this scope, $\varsigma_{\mu_{\tilde{A}_S}}$, $\varsigma_{\nu_{\tilde{A}_S}}$, and $\varsigma_{h_{\tilde{A}_S}}$ refer to the membership, nonmembership hesitant degrees. Furthermore, quantum spherical fuzzy numbers ζ are indicated in Eqs. (7) and (8).

$$\zeta = \left[\varsigma_{\mu} \cdot e^{j2\pi \cdot \alpha}, \varsigma_{\nu} \cdot e^{j2\pi \cdot \gamma}, \varsigma_{h} \cdot e^{j2\pi \cdot \beta} \right] \tag{7}$$

$$\varphi^2 = |\varsigma_{\mu}(|u_i \rangle)| \tag{8}$$

Golden cut is considered in this proposed model to compute the degrees. Equations (9) and (10) underline the details of this situation.

$$G = \frac{a}{b} \tag{9}$$

$$G = \frac{1 + \sqrt{5}}{2} = 1.618 \dots \tag{10}$$

Equation (11) highlights the phase angle of the quantum spherical fuzzy sets.

$$\alpha = |S_{\mu}(|u_i >)| \tag{11}$$

Equations (12) and (13) show the phase angle of nonmember degrees γ and hesitancy degrees β .

$$\gamma = \frac{\alpha}{G} \tag{12}$$

$$\beta = 1 - \alpha - \gamma \tag{13}$$

Equations (14)–(17) present the general calculations.

$$\lambda * \tilde{A}_S = \left\{ \left(1 - \left(1 - S_{\mu_{\bar{A}}} \right)^{\lambda} \right)^{\frac{1}{2}} e^{j2\pi \cdot \left(1 - \left(\frac{\alpha_{\bar{A}}}{2\pi} \right)^2 \right)^{\lambda}}, S_{\nu_{\bar{A}}}^{\lambda} e^{j2\pi \cdot \left(\frac{\gamma_{\bar{A}}}{2\pi} \right)^{\lambda}}, \right. \\ \left. \left(\left(1 - S_{h_{\bar{A}}} \right)^{\lambda} - \left(1 - S_{\mu_{\bar{A}}} - S_{h_{\bar{A}}} \right)^{\lambda} \right)^{\frac{1}{2}} e^{j2\pi \cdot \left(\left(1 - \left(\frac{\beta_{\bar{A}}}{2\pi} \right)^2 \right)^{\lambda} - \left(1 - \left(\frac{\alpha_{\bar{A}}}{2\pi} \right)^2 - \left(\frac{\beta_{\bar{A}}}{2\pi} \right)^2 \right)^{\lambda}} \right)^{\frac{1}{2}} \right\}_{\lambda > 0} \tag{14}$$

$$\tilde{A}_S^{\lambda} = \left\{ S_{\mu_{\bar{A}}}^{\lambda} e^{j2\pi \cdot \left(\frac{\alpha_{\bar{A}}}{2\pi} \right)^{\lambda}}, \left(1 - \left(1 - S_{\nu_{\bar{A}}} \right)^{\lambda} \right)^{\frac{1}{2}} e^{j2\pi \cdot \left(1 - \left(\frac{\gamma_{\bar{A}}}{2\pi} \right)^2 \right)^{\lambda}} \right)^{\frac{1}{2}}, \\ \left(\left(1 - S_{\nu_{\bar{A}}} \right)^{\lambda} - \left(1 - S_{\nu_{\bar{A}}} - S_{h_{\bar{A}}} \right)^{\lambda} \right)^{\frac{1}{2}} e^{j2\pi \cdot \left(\left(1 - \left(\frac{\gamma_{\bar{A}}}{2\pi} \right)^2 \right)^{\lambda} - \left(1 - \left(\frac{\gamma_{\bar{A}}}{2\pi} \right)^2 - \left(\frac{\beta_{\bar{A}}}{2\pi} \right)^2 \right)^{\lambda}} \right)^{\frac{1}{2}} \right\}_{\lambda > 0} \tag{15}$$

$$\tilde{A}_S \oplus \tilde{B}_S = \left\{ \left(S_{\mu_{\bar{A}}}^2 + S_{\mu_{\bar{B}}}^2 - S_{\mu_{\bar{A}}} S_{\mu_{\bar{B}}} \right)^{\frac{1}{2}} e^{j2\pi \cdot \left(\left(\frac{\alpha_{\bar{A}}}{2\pi} \right)^2 + \left(\frac{\alpha_{\bar{B}}}{2\pi} \right)^2 - \left(\frac{\alpha_{\bar{A}}}{2\pi} \right)^2 \left(\frac{\alpha_{\bar{B}}}{2\pi} \right)^2 \right)^{\frac{1}{2}}, \right. \\ S_{\nu_{\bar{A}}} S_{\nu_{\bar{B}}} e^{j2\pi \cdot \left(\left(\frac{\gamma_{\bar{A}}}{2\pi} \right) \left(\frac{\gamma_{\bar{B}}}{2\pi} \right) \right)}, \left(\left(1 - S_{\mu_{\bar{B}}} \right)^2 S_{h_{\bar{A}}}^2 + \left(1 - S_{\mu_{\bar{A}}} \right)^2 S_{h_{\bar{B}}}^2 - S_{h_{\bar{A}}}^2 S_{h_{\bar{B}}}^2 \right) \\ \left. \frac{1}{2} e^{j2\pi \cdot \left(\left(1 - \left(\frac{\beta_{\bar{B}}}{2\pi} \right)^2 \right) \left(\frac{\beta_{\bar{A}}}{2\pi} \right)^2 + \left(1 - \left(\frac{\alpha_{\bar{A}}}{2\pi} \right)^2 \right) \left(\frac{\beta_{\bar{B}}}{2\pi} \right)^2 - \left(\frac{\beta_{\bar{A}}}{2\pi} \right)^2 \left(\frac{\beta_{\bar{B}}}{2\pi} \right)^2 \right)^{\frac{1}{2}} \right\} \tag{16}$$

$$\begin{aligned}
 \tilde{A}_S \otimes \tilde{B}_S = & \left\{ \begin{aligned}
 & s_{\mu_A} s_{\mu_B} e^{j2\pi \cdot \left(\frac{\alpha_A}{2\pi}\right) \left(\frac{\alpha_B}{2\pi}\right)}, \left(s_{v_A}^2 + s_{v_B}^2 - s_{v_A}^2 s_{v_B}^2\right)^{\frac{1}{2}} \\
 & e^{j2\pi \cdot \left(\left(\frac{\gamma_A}{2\pi}\right)^2 + \left(\frac{\gamma_B}{2\pi}\right)^2 - \left(\frac{\gamma_A}{2\pi}\right)^2 \left(\frac{\gamma_B}{2\pi}\right)^2\right)^{\frac{1}{2}}}, \left(\left(1 - s_{v_B}^2\right) s_{h_A}^2 + \left(1 - s_{v_A}^2\right) s_{h_B}^2 - s_{h_A}^2 s_{h_B}^2\right) \\
 & \frac{1}{2} e^{j2\pi \cdot \left(\left(1 - \left(\frac{\gamma_B}{2\pi}\right)^2\right) \left(\frac{\beta_A}{2\pi}\right)^2 + \left(1 - \left(\frac{\gamma_A}{2\pi}\right)^2\right) \left(\frac{\beta_B}{2\pi}\right)^2 - \left(\frac{\beta_A}{2\pi}\right)^2 \left(\frac{\beta_B}{2\pi}\right)^2\right)^{\frac{1}{2}}} \end{aligned} \right\}
 \end{aligned}
 \tag{17}$$

The extension of DEMATEL

DEMATEL is used to weight different determinants. First, evaluations are provided by the decision-makers. Equation (18) denotes the decision matrix (Kou et al. 2024).

$$S_k = \begin{bmatrix} 0 & s_{12} & \cdots & \cdots & s_{1n} \\ s_{21} & 0 & \cdots & \cdots & s_{2n} \\ \vdots & \vdots & \ddots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & \cdots & 0 \end{bmatrix}
 \tag{18}$$

Equation (19) demonstrates the aggregated values

$$\begin{aligned}
 S = & \left\{ \begin{aligned}
 & \left[1 - \prod_{i=1}^k \left(1 - s_{\mu_i}^2\right)^{\frac{1}{k}} \right]^{\frac{1}{2}} e^{2\pi \cdot \left[1 - \prod_{i=1}^k \left(1 - \left(\frac{\alpha_i}{2\pi}\right)^2\right)^{\frac{1}{k}} \right]^{\frac{1}{2}}}, \\
 & \prod_{i=1}^k s_{v_i}^{\frac{1}{k}} e^{2\pi \cdot \prod_{i=1}^k \left(\frac{\gamma_i}{2\pi}\right)^{\frac{1}{k}}}, \left[\prod_{i=1}^k \left(1 - s_{\mu_i}^2\right)^{\frac{1}{k}} - \prod_{i=1}^k \left(1 - s_{\mu_i}^2 - s_{h_i}^2\right)^{\frac{1}{k}} \right] \\
 & \frac{1}{2} e^{2\pi \cdot \left[\prod_{i=1}^k \left(1 - \left(\frac{\alpha_i}{2\pi}\right)^2\right)^{\frac{1}{k}} - \prod_{i=1}^k \left(1 - \left(\frac{\alpha_i}{2\pi}\right)^2 - \left(\frac{\beta_i}{2\pi}\right)^2\right)^{\frac{1}{k}} \right]^{\frac{1}{2}}} \end{aligned} \right\}
 \end{aligned}
 \tag{19}$$

The defuzzified values are defined in Eq. (20).

$$Def\ s_i = s_{\mu_i} + s_{h_i} \left(\frac{s_{\mu_i}}{s_{\mu_i} + s_{v_i}} \right) + \left(\frac{\alpha_i}{2\pi} \right) + \left(\frac{\gamma_i}{2\pi} \right) \left(\frac{\left(\frac{\alpha_i}{2\pi}\right)}{\left(\frac{\alpha_i}{2\pi}\right) + \left(\frac{\beta_i}{2\pi}\right)} \right)
 \tag{20}$$

The direct relation matrix is normalized in Eqs. (21) and (22).

$$B = \frac{S}{\max_{1 \leq i \leq n} \sum_{j=1}^n s_{ij}}
 \tag{21}$$

$$0 \leq b_{ij} \leq 1
 \tag{22}$$

Equation (23) indicates the details of the total relation matrix.

$$\lim_{k \rightarrow \infty} (B + B^2 + \dots + B^k) = B(I - B)^{-1} \tag{23}$$

The total cause and effect are computed by Eqs. (24) and (25).

$$D = \left[\sum_{j=1}^n e_{ij} \right]_{n \times 1} \tag{24}$$

$$E = \left[\sum_{i=1}^n e_{ij} \right]_{1 \times n} \tag{25}$$

Equation (26) identifies the causal directions.

$$\alpha = \frac{\sum_{i=1}^n \sum_{j=1}^n [e_{ij}]}{N} \tag{26}$$

The extension of TOPSIS

TOPSIS is used for alternative ranking. Evaluations are collected for constructing the decision matrix in Eq. (27) (Sathyan et al. 2023).

$$X_k = \begin{bmatrix} 0 & X_{12} & \dots & \dots & X_{1m} \\ X_{21} & 0 & \dots & \dots & X_{2m} \\ \vdots & \vdots & \ddots & \dots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \dots & \dots & 0 \end{bmatrix} \tag{27}$$

Normalized values are created with Eq. (28).

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^m X_{ij}^2}} \tag{28}$$

The v_{ij} values are weighted by Eq. (29).

$$v_{ij} = w_{ij} \times r_{ij} \tag{29}$$

The positive (A^+) and negative (A^-) solutions are shown with Eqs. (30) and (31).

Table 1 Evaluation scales of decision makers

For criteria	For alternatives	Fuzzy sets
No (NIFL)	Weakest (WKT)	$[\sqrt{0.16}e^{j2\pi \cdot 0.4}, \sqrt{0.10}e^{j2\pi \cdot 0.25}, \sqrt{0.74}e^{j2\pi \cdot 0.35}]$
some (SIFL)	Poor (PR)	$[\sqrt{0.20}e^{j2\pi \cdot 0.45}, \sqrt{0.13}e^{j2\pi \cdot 0.28}, \sqrt{0.67}e^{j2\pi \cdot 0.27}]$
medium (MIFL)	Fair (FR)	$[\sqrt{0.25}e^{j2\pi \cdot 0.50}, \sqrt{0.15}e^{j2\pi \cdot 0.31}, \sqrt{0.60}e^{j2\pi \cdot 0.19}]$
high (HIFL)	Good (GD)	$[\sqrt{0.30}e^{j2\pi \cdot 0.55}, \sqrt{0.19}e^{j2\pi \cdot 0.34}, \sqrt{0.51}e^{j2\pi \cdot 0.11}]$
very high (VHIFL)	Best (BST)	$[\sqrt{0.36}e^{j2\pi \cdot 0.6}, \sqrt{0.22}e^{j2\pi \cdot 0.37}, \sqrt{0.42}e^{j2\pi \cdot 0.03}]$

Table 2 Expert choices for the relation matrix

Criteria	EFS	IS	OTA	CCT	ARM	TA
EXPT 1						
EFS		SIFL	HIFL	HIFL	MIFL	HIFL
IS	SIFL		HIFL	HIFL	HIFL	SIFL
OTA	HIFL	HIFL		VHIFL	HIFL	MIFL
CCT	MIFL	SIFL	VHIFL		HIFL	HIFL
ARM	MIFL	HIFL	HIFL	HIFL		SIFL
TA	HIFL	MIFL	MIFL	VHIFL	SIFL	
EXPT 2						
EFS		SIFL	MIFL	HIFL	MIFL	VHIFL
IS	SIFL		VHIFL	HIFL	HIFL	SIFL
OTA	MIFL	HIFL		VHIFL	HIFL	HIFL
CCT	MIFL	SIFL	VHIFL		HIFL	HIFL
ARM	MIFL	HIFL	HIFL	HIFL		SIFL
TA	MIFL	VHIFL	MIFL	SIFL	SIFL	
EXPT 3						
EFS		HIFL	VHIFL	VHIFL	SIFL	HIFL
IS	HIFL		HIFL	HIFL	HIFL	SIFL
OTA	HIFL	HIFL		VHIFL	VHIFL	VHIFL
CCT	MIFL	SIFL	VHIFL		HIFL	VHIFL
ARM	SIFL	HIFL	HIFL	HIFL		SIFL
TA	VHIFL	MIFL	HIFL	SIFL	MIFL	

Table 3 Overall fuzzy results of the financial innovation-based characteristics

	EFS	IS	OTA	CCT	ARM	TA
EFS		$\begin{bmatrix} \sqrt{0.24}e^{j2\pi \cdot 0.48} \\ \sqrt{0.14}e^{j2\pi \cdot 0.30} \\ \sqrt{0.62}e^{j2\pi \cdot 0.22} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.31}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.13} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.32}e^{j2\pi \cdot 0.57} \\ \sqrt{0.20}e^{j2\pi \cdot 0.35} \\ \sqrt{0.48}e^{j2\pi \cdot 0.09} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.24}e^{j2\pi \cdot 0.48} \\ \sqrt{0.14}e^{j2\pi \cdot 0.30} \\ \sqrt{0.62}e^{j2\pi \cdot 0.22} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.32}e^{j2\pi \cdot 0.57} \\ \sqrt{0.20}e^{j2\pi \cdot 0.35} \\ \sqrt{0.48}e^{j2\pi \cdot 0.09} \end{bmatrix}$
IS	$\begin{bmatrix} \sqrt{0.24}e^{j2\pi \cdot 0.48} \\ \sqrt{0.14}e^{j2\pi \cdot 0.30} \\ \sqrt{0.62}e^{j2\pi \cdot 0.22} \end{bmatrix}$		$\begin{bmatrix} \sqrt{0.32}e^{j2\pi \cdot 0.57} \\ \sqrt{0.20}e^{j2\pi \cdot 0.35} \\ \sqrt{0.48}e^{j2\pi \cdot 0.09} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.11} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.11} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.20}e^{j2\pi \cdot 0.45} \\ \sqrt{0.13}e^{j2\pi \cdot 0.28} \\ \sqrt{0.67}e^{j2\pi \cdot 0.27} \end{bmatrix}$
OTA	$\begin{bmatrix} \sqrt{0.29}e^{j2\pi \cdot 0.54} \\ \sqrt{0.18}e^{j2\pi \cdot 0.33} \\ \sqrt{0.54}e^{j2\pi \cdot 0.15} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.11} \end{bmatrix}$		$\begin{bmatrix} \sqrt{0.36}e^{j2\pi \cdot 0.60} \\ \sqrt{0.22}e^{j2\pi \cdot 0.37} \\ \sqrt{0.42}e^{j2\pi \cdot 0.03} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.32}e^{j2\pi \cdot 0.57} \\ \sqrt{0.20}e^{j2\pi \cdot 0.35} \\ \sqrt{0.48}e^{j2\pi \cdot 0.09} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.31}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.13} \end{bmatrix}$
CCT	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi \cdot 0.50} \\ \sqrt{0.15}e^{j2\pi \cdot 0.31} \\ \sqrt{0.60}e^{j2\pi \cdot 0.19} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.20}e^{j2\pi \cdot 0.45} \\ \sqrt{0.13}e^{j2\pi \cdot 0.28} \\ \sqrt{0.67}e^{j2\pi \cdot 0.27} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.36}e^{j2\pi \cdot 0.60} \\ \sqrt{0.22}e^{j2\pi \cdot 0.37} \\ \sqrt{0.42}e^{j2\pi \cdot 0.03} \end{bmatrix}$		$\begin{bmatrix} \sqrt{0.30}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.11} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.32}e^{j2\pi \cdot 0.57} \\ \sqrt{0.20}e^{j2\pi \cdot 0.35} \\ \sqrt{0.48}e^{j2\pi \cdot 0.09} \end{bmatrix}$
ARM	$\begin{bmatrix} \sqrt{0.24}e^{j2\pi \cdot 0.48} \\ \sqrt{0.14}e^{j2\pi \cdot 0.30} \\ \sqrt{0.62}e^{j2\pi \cdot 0.22} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.11} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.11} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.11} \end{bmatrix}$		$\begin{bmatrix} \sqrt{0.20}e^{j2\pi \cdot 0.45} \\ \sqrt{0.13}e^{j2\pi \cdot 0.28} \\ \sqrt{0.67}e^{j2\pi \cdot 0.27} \end{bmatrix}$
TA	$\begin{bmatrix} \sqrt{0.31}e^{j2\pi \cdot 0.55} \\ \sqrt{0.19}e^{j2\pi \cdot 0.34} \\ \sqrt{0.51}e^{j2\pi \cdot 0.13} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.29}e^{j2\pi \cdot 0.54} \\ \sqrt{0.18}e^{j2\pi \cdot 0.33} \\ \sqrt{0.54}e^{j2\pi \cdot 0.15} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.27}e^{j2\pi \cdot 0.52} \\ \sqrt{0.16}e^{j2\pi \cdot 0.32} \\ \sqrt{0.57}e^{j2\pi \cdot 0.18} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.27}e^{j2\pi \cdot 0.52} \\ \sqrt{0.16}e^{j2\pi \cdot 0.32} \\ \sqrt{0.57}e^{j2\pi \cdot 0.18} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.22}e^{j2\pi \cdot 0.47} \\ \sqrt{0.13}e^{j2\pi \cdot 0.29} \\ \sqrt{0.65}e^{j2\pi \cdot 0.25} \end{bmatrix}$	

$$A^+ = \{v_{1j}, v_{2j}, \dots, v_{mj}\} = \{\max v_{1j} \text{ for } \forall j \in n\}, \tag{30}$$

$$A^- = \{v_{1j}, v_{2j}, \dots, v_{mj}\} = \{\min v_{ij} \text{ for } \forall j \in n\}. \tag{31}$$

Equations (32) and (33) identify the distances to the best (D_i^+) and worst alternatives (D_i^-).

$$D_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - A_j^+)^2}, \tag{32}$$

$$D_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - A_j^-)^2}. \tag{33}$$

Equation (34) defines the relative closeness to the ideal solutions (RC_i).

$$RC_i = \frac{D_i^-}{D_i^+ + D_i^-}. \tag{34}$$

Table 4 Defuzzified values of relation matrix

	EFS	IS	OTA	CCT	ARM	TA
EFS	0.000	1.263	1.259	1.245	1.243	1.245
IS	1.263	0.000	1.245	1.236	1.236	1.236
OTA	1.243	1.236	0.000	1.236	1.245	1.259
CCT	1.236	1.236	1.236	0.000	1.236	1.245
ARM	1.243	1.236	1.236	1.236	0.000	1.236
TA	1.259	1.266	1.243	1.297	1.243	0.000

Table 5 Normalized scores of the relation matrix

	EFS	IS	OTA	CCT	ARM	TA
EFS	0.000	0.200	0.200	0.197	0.197	0.197
IS	0.200	0.000	0.197	0.196	0.196	0.196
OTA	0.197	0.196	0.000	0.196	0.197	0.200
CCT	0.196	0.196	0.196	0.000	0.196	0.197
ARM	0.197	0.196	0.196	0.196	0.000	0.196
TA	0.200	0.201	0.197	0.206	0.197	0.000

Table 6 Total values of the relation matrix, weights, and the directions

	EFS	IS	OTA	CCT	ARM	TA	Weights	Directions
EFS	13.181	13.334	13.305	13.357	13.272	13.307	0.1671	EFS → (IS,OTA,CCT,ARM,TA)
IS	13.279	13.099	13.235	13.287	13.203	13.237	0.1666	IS → (EFS, CCT)
OTA	13.284	13.270	13.077	13.294	13.211	13.247	0.1665	OTA → (EFS,IS,CCT,TA)
CCT	13.229	13.216	13.187	13.076	13.157	13.192	0.1665	–
ARM	13.225	13.211	13.182	13.235	12.988	13.186	0.1659	–
TA	13.439	13.426	13.394	13.454	13.364	13.234	0.1675	TA → (EFS,IS,OTA,CCT,ARM)

Table 7 Expert choices for the decision matrix

	EFS	IS	OTA	CCT	ARM	TA
EXPT 1						
EC1	FR	FR	BST	PR	PR	BST
EC2	PR	FR	FR	BST	BST	GD
EC3	FR	PR	GD	PR	FR	PR
EC4	PR	BST	FR	PR	BST	GD
EC5	BST	PR	BST	PR	BST	FR
EC6	FR	BST	GD	BST	GD	GD
EC7	GD	FR	PR	FR	PR	GD
EC8	BST	GD	BST	GD	BST	GD
EC9	BST	FR	BST	GD	BST	GD
EC10	GD	FR	FR	PR	BST	FR
EXPT 2						
EC1	PR	PR	BST	PR	PR	BST
EC2	PR	FR	FR	BST	BST	FR
EC3	PR	PR	GD	PR	FR	PR
EC4	PR	BST	FR	PR	BST	FR
EC5	FR	PR	FR	PR	BST	FR
EC6	FR	BST	GD	BST	GD	GD
EC7	FR	FR	PR	PR	PR	GD
EC8	FR	FR	FR	GD	BST	GD
EC9	BST	FR	FR	GD	FR	FR
EC10	GD	FR	FR	FR	FR	FR
EXPT 3						
EC1	PR	FR	BST	PR	PR	BST
EC2	PR	GD	FR	FR	GD	GD
EC3	PR	PR	GD	PR	FR	FR
EC4	PR	BST	FR	PR	GD	GD
EC5	BST	PR	FR	PR	BST	FR
EC6	FR	BST	BST	BST	BST	GD
EC7	GD	PR	PR	BST	PR	GD
EC8	BST	GD	BST	GD	BST	BST
EC9	BST	PR	BST	GD	PR	GD
EC10	GD	FR	FR	BST	BST	FR

Analysis results

In this stage, the weighting results of the criteria for the financial innovation-based characteristics of stock market efficiency. Six criteria of financial innovation characteristics are defined: “excellence of financial system” (EFS) (Patra and Hiremath 2024), “information symmetry” (IS) (Jaquart et al. 2023), “operational timeliness of agencies” (Meng et al. 2023), “competitive costs of transactions” (CCT) (Lee et al. 2024), “accurate risk management” (ARM) (Meng et al. 2023), and “tax advantages” (TA) (Gao et al. 2024). First, three experts (EXPT) are assigned to get their evaluations on the criteria relations and the decision matrix of emerging economies. These people have at least 25 years of working experience and work as general managers in international financial institutions. The linguistic evaluations are collected using the defined scales, and the results are presented (Tables 1 and 2).

Table 10 Normalized values of decision matrix

	EFS	IS	OTA	CCT	ARM	TA
EC1	0.316	0.317	0.314	0.313	0.313	0.315
EC2	0.314	0.317	0.314	0.321	0.316	0.317
EC3	0.316	0.315	0.314	0.313	0.313	0.317
EC4	0.314	0.315	0.314	0.313	0.316	0.317
EC5	0.322	0.315	0.321	0.313	0.313	0.315
EC6	0.314	0.315	0.316	0.313	0.316	0.315
EC7	0.316	0.317	0.314	0.325	0.313	0.315
EC8	0.322	0.317	0.322	0.313	0.313	0.318
EC9	0.314	0.317	0.322	0.313	0.326	0.317
EC10	0.314	0.315	0.314	0.325	0.322	0.315

Table 11 Weighted values of decision matrix

	EFS	IS	OTA	CCT	ARM	TA
EC1	0.053	0.053	0.052	0.052	0.052	0.053
EC2	0.052	0.053	0.052	0.053	0.052	0.053
EC3	0.053	0.053	0.052	0.052	0.052	0.053
EC4	0.052	0.053	0.052	0.052	0.052	0.053
EC5	0.054	0.053	0.053	0.052	0.052	0.053
EC6	0.052	0.053	0.053	0.052	0.052	0.053
EC7	0.053	0.053	0.052	0.054	0.052	0.053
EC8	0.054	0.053	0.054	0.052	0.052	0.053
EC9	0.052	0.053	0.054	0.052	0.054	0.053
EC10	0.052	0.053	0.052	0.054	0.053	0.053

The next steps define the defuzzification process of the fuzzy numbers using the score function of the integrated quantum decision-making approach. The defuzzified scores and the weighted results are stated in Tables 4 and 5, respectively.

At the computation process’s final weighting step, the relation matrix’s total values, directions, ways, and weights are illustrated for the financial innovation-based characteristics of stock market efficiency. Table 6 presents the comprehensive results.

Table 7 shows the total values of the relation matrix and the criteria weights and their impacts. The weighting values are obtained using the normalized sum of D and E values. The impact directions among the criteria are selected by considering the average value of the total relation matrix. Accordingly, the possible impact of each criterion is determined in terms of this assumption. The results show that TA has the highest importance among the criteria set, while ARM has the weakest priority. Similarly, EFS and TA influence the other criteria most, as CCT and ARM do not affect other criteria. Thus, tax-based characteristics of financial innovation have a priority role in the stock market efficiency; however, risk management and transaction-oriented strategies are less prioritized in financial innovation policies.

In the second part of stage 2, the selected economies entitled Chile (EC1), Belgium (EC2), Mexico (EC3), Russia (EC4), Norway (EC5), New Zealand (EC6), Germany

Table 12 Ranking performance of the selected economies

Economies	D+	D+	RCi	Ranking
EC1	0.003	0.000	0.104	10
EC2	0.003	0.002	0.371	6
EC3	0.003	0.000	0.105	9
EC4	0.003	0.001	0.145	8
EC5	0.003	0.002	0.393	5
EC6	0.003	0.001	0.147	7
EC7	0.003	0.002	0.431	3
EC8	0.003	0.002	0.418	4
EC9	0.002	0.003	0.503	2
EC10	0.002	0.002	0.534	1

(EC7), United Kingdom (EC8), USA (EC9), and Switzerland (EC10) are ranked concerning the financial innovation-based characteristics of stock market efficiency. The experts provided their choices on the decision matrix, as seen in Table 1. The linguistic choices are dedicated in Table 12.

Similarly, the fuzzy numbers of the linguistic evaluations from the experts are defined, and the average scores of fuzzy numbers with the quantum spherical fuzzy sets are computed, as shown in Table 8.

In the next steps, the decision matrix’s normalized and weighted values are computed using the defuzzified values of the fuzzy numbers. Therefore, the defuzzified, normalized, and weighted values are given respectively in Tables 9, 10 and 11.

Finally, the ranking results of the selected economies are determined by using the values of RCi (Table 12).

Table 12 shows that the ranking results as Switzerland (EC10), USA (EC9), Germany (EC7), United Kingdom (EC8), Norway (EC5), Belgium (EC2), New Zealand (EC6), Russia (EC4), Mexico (EC3), and Chile (EC1). According to the ranking of the economies, EC10 (Switzerland) has the best performance on the financial innovation-based characteristics of stock market efficiency, while EC1 (Chile) is the weakest country.

Discussion

Providing tax advantages is the most critical factor in ensuring stock market efficiency. TA help businesses reduce their costs significantly, which attracts investors to the stock markets and encourages them to invest; thus, the number of investors entering the market may significantly increase. This situation contributes significantly to increasing liquidity in the market. Another positive effect of the tax advantage is that it can include new customers into the system; thus, it increases liquidity by increasing the number of players in the market. Chen et al. (2024) and Htun et al. (2023) indicated that TA could be particularly attractive for long-term investments. It is possible to ensure market stability by making long-term investments. Conversely, Villena and Araneda (2024) and Moews (2023) identified that TA enable investors to diversify their portfolios; thus, managing risks in the market is easier. Furthermore, Iordache (2024) denoted that TA make

domestic markets more attractive to international investors. This situation allows the country's economy to grow (An et al. 2020, 2024; Chen et al. 2024).

The excellence of the financial system is critical in ensuring stock market efficiency. Increasing the market's liquidity is possible by ensuring the financial system's perfection. Thanks to high liquidity, the efficiency of these markets can be increased. Furthermore, an excellent financial system helps stock prices reflect available information accurately and quickly. In other words, correct pricing is possible by ensuring the perfection of the financial system. Moreover, Li et al. (2024) showed that the perfection of the financial system contributes significantly to reducing information asymmetry. The biggest advantage of this situation is that it increases the efficiency of the stock market. Additionally, Wilson (2023) demonstrated that thanks to a developed financial system, it is possible to increase transaction security, allowing the stability in the market to increase (Plas-tun et al. 2024). Furthermore, Azeem et al. (2023) defined that the effectiveness of risk management can be increased with the development of the financial system, which helps reduce losses caused by volatility in the market (Li et al. 2024).

Conclusion

This study aims to evaluate the financial innovation-based characteristics of stock market efficiency. In this scope, the main research question of this study is to identify which factors should be prioritized to improve the stock market. Within this context, we created a novel fuzzy decision-making model consisting of two stages. First, selected criteria for the financial innovation-based characteristics of stock market efficiency are weighted. In this process, quantum spherical fuzzy sets based on DEMATEL are considered. In the second stage, selected economies are ranked using the TOPSIS approach. The findings indicate that providing TA is the most critical factor in ensuring stock market efficiency. Moreover, the excellence of the financial system is critical in ensuring stock market efficiency. In this context, it is possible to provide TA, especially for long-term investments; thus, long-term investments can be increased, significantly increasing the market's stability.

TA must be provided to ensure stock market efficiency. It is possible to offer some policy suggestions to achieve this goal. In this context, it is possible to provide TA, especially for long-term investments; thus, long-term investments can be increased, significantly increasing the market's stability. Providing TA for investments made for the first time is also very important. Applying low tax rates to new investors increases investments in the market. Thus, it becomes easier to increase liquidity in the market. The excellence of the financial system is also critical in ensuring stock market efficiency. Various policy recommendations can be implemented to achieve this excellence. Ensuring a developed market structure significantly supports the achievement of this goal. In this way, increasing liquidity by increasing transaction speed is possible. Establishing an effective audit system also increases the financial system's perfection; thus, investors' confidence in the market will increase, increasing the liquidity in the market.

The main contribution of this study is that the DEMATEL technique in calculating criterion weights in the decision-making analysis process provides some advantages. With the help of this situation, the causal directions between these items can be considered. In this way, it is possible to determine the most accurate strategies. The biggest limitation

of this study is that the TOPSIS methodology is considered to rank alternatives. Despite many advantages, this technique has also been criticized by many scholars. This situation is also similar to other existing ranking techniques. Due to this issue, a new ranking technique can be introduced in future studies while considering these criticisms. Similarly, the experts' evaluations are considered to have the same coefficient. Nevertheless, these experts can have different demographic factors. Therefore, future research can construct a new decision-making model, and the weights of these experts can be computed.

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Author contributions

The problem is proposed by AM. The solving method is proposed by DR and AF. The method is applied by HD and SY. The writing of manuscript is done by AM. All author(s) read and approved the final manuscript.

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This manuscript does not require ethical approval and content to participate since it does not contain any human participate, human data or human tissue.

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The author declare that they have no competing interests.

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