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Research Article

Understanding the market potential of crypto mining with quantum mechanics and golden cut-based picture fuzzy rough sets

Hasan Dincer [a,b], Serhat Yüksel [a,b], Gabor Pinter [c,d,*], Alexey Mikhaylov [e]

[a] School of Business, Istanbul Medipol University, Istanbul 34810, Turkey
[b] Department of Economics and Management, Khazar University, Baku AZ1096, Republic of Azerbaijan
[c] University Center for Circular Economy, Renewable Energy Research Group, University of Pannonia, Veszprém 8200, Hungary
[d] Western Caspian University, Baku AZ1001, Republic of Azerbaijan
[e] Financial University Under the Government of the Russian Federation, Moscow 125167, Russia

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ABSTRACT

Significant improvements should be made to increase the market potential of crypto mining. However, it is not financially feasible to make too many improvements because all actions lead to cost increases. In this context, it is necessary to determine the factors that most affect this process. Accordingly, the purpose of this study is to understand the main indicators that can improve the market potential of crypto mining activities. Therefore, the main research question of this study is to identify which factors should be prioritized while generating appropriate strategies to increase these activities. In this context, a new model has been constructed to answer this question. First, significant indicators are identified based on the evaluation of the literature. After that, these factors are weighted via quantum picture fuzzy rough set-based M-SWARA. The main contribution of this study is the generation of a new decision-making model to understand the key issues related to the market potential of crypto mining activities. The M-SWARA model is taken into consideration for criteria weighting. Owing to this issue, the causal relationships between the items can be identified. The findings demonstrate that reducing energy costs emerges as the most important factor for improving the market potential of the crypto mining industry. Furthermore, technological developments also play an important role in this regard.

1. Introduction

The main purpose of crypto mining is the creation of cryptocurrencies. Owing to this situation, cryptocurrencies can enter the market. In addition, it is possible to ensure the security of the blockchain in this process. Crypto mining has several important advantages. One of the biggest advantages of cryptocurrencies is that they provide financial independence to countries. Owing to this mining, financial transactions can be carried out without being dependent on a central authority [1]. Similarly, owing to the use of blockchain infrastructure in crypto mining, transactions can be carried out more securely. This situation allows more investors to trade in the market. On the other hand, in crypto mining, miners perform intensive transactions through computers. This situation has also been criticized because of several negative environmental effects. A large amount of energy is consumed in the crypto mining process. This situation has led to faster consumption of natural resources. Similarly, legal rules in some countries also pose obstacles to the development of crypto mining. For example, the costs of crypto mining may increase in the case of additional taxation.

Crypto mining activities have huge market potential. However, many different issues need to be taken into consideration for the development of crypto mining. Technological development is an issue that should be given priority in this regard. Owing to the development of technology, the efficiency of crypto mining can increase. This contributes to significantly reducing the costs of transactions. The effectiveness of legal regulations is another situation that supports the increase in the market potential of crypto mining [2]. Owing to the adequacy of these regulations, investors prefer these products more. On the other hand, the profitability of crypto mining is directly related to the market value of the cryptocurrency being mined. When the profitability of these transactions increases, more investors use these products. Reducing energy costs is also important for the development of the market potential of crypto mining. One of the biggest cost items of crypto mining is related to the energy used. Therefore, it is possible to increase the profitability

* Corresponding author.
E-mail addresses: hdincer@medipol.edu.tr (H. Dincer), serhatyuksel@medipol.edu.tr (S. Yüksel), prof7657@ya.ru (G. Pinter), alexeyfa@ya.ru (A. Mikhaylov).

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of crypto mining by reducing these costs. In this context, ways to perform crypto mining with less energy consumption should be determined.

Many factors affect the market potential of crypto mining. This situation makes it difficult to make the necessary improvements to this process. The main reason for this is that these improvements lead to an increase in cost. Therefore, it is not financially feasible to make too many improvements. Therefore, it is necessary to focus on fewer and more important factors [3]. In this context, it is necessary to determine the factors that most affect the development of the market potential of crypto mining. However, there are a limited number of studies on this subject in the literature. This situation increases the need for new studies in this field. Otherwise, effective measures will not be taken to develop the market potential of this mining. With this new study, it will be possible to develop the most accurate investment strategies. Thus, it becomes easier to fill this gap in the literature on this subject.

Accordingly, the purpose of this study is to understand the main indicators that can improve the market potential of crypto mining activities. Therefore, the main research question of this study is to identify which factors should be prioritized while generating appropriate strategies to increase these activities. For this purpose, a new model has been generated to answer this question. First, significant indicators are identified based on the evaluation of the literature. After that, these factors are weighted via quantum picture fuzzy rough set-based M-SWARA. The main motivation of this study is the need for a comprehensive examination to provide market potential for crypto mining activities. PESTEL, SWOT, and balanced scorecard evaluations are considered in the literature for this situation. Similarly, decision-making models are also used in this framework. However, there are also some criticisms regarding these models. In summary, there is a need for a new model to evaluate this situation.

The main contribution of this study is the generation of a new decision-making model to understand the key issues related to the market potential of crypto mining activities. Compared with the previously generated models, the proposed model has several advantages. The details of these superiorities are given below. (i) The M-SWARA model is taken into consideration for criteria weighting. This methodology is created by making some improvements to the SWARA. Owing to these issues, the causal relationships between the items can be identified. The main indicators of the market potential of crypto mining activities can have an impact on each other. Therefore, to define the main determinants of this situation, causal directions should be considered. Because of this condition, the M-SWARA technique provides an opportunity to make better evaluations. (ii) Quantum theory and picture fuzzy rough sets are integrated in this proposed model. This integration provides some important advantages for this model. Quantum theory can make sensitive predictions. Hence, this theory is integrated into the decision-making methodology. Hence, it can be more possible to minimize uncertainties. On the other hand, picture fuzzy rough sets can be very helpful for making more effective evaluations due to considering a wide range of datasets.

The remainder of this paper is structured as follows: The literature review is presented in Section 2. Section 3 consists of the main steps of the proposed model. The analysis results are presented in Section 4. Section 5 and Section 6 present the discussion and conclusion of this work, respectively.

2. Literature review

Technological developments play an important role in developing the market potential of the crypto mining industry. With the use of new technologies, it is possible to use less energy in the process [4]. This contributes significantly to reducing costs. Similarly, the costs of equipment used with advanced technologies may also decrease. This issue allows the profitability of transactions to increase [5]. Technological advances can increase the security of cryptocurrency networks. According to Ref. [6], owing to these systems, stronger encryption techniques can be used. This situation helps make network communication more secure. Estecahandy [7] determined that the biggest advantage of this event is that it increases user trust. On the other hand, Yu et al. [8] reported that technological advances can provide innovative solutions in mining processes. This condition allows data processing methods to be more effective. Thus, it becomes more possible to develop the market potential of the crypto mining industry.

Legal effectiveness is highly important in developing the market potential of the crypto mining industry. Crypto mining is a very new practice for many countries. Therefore, legal regulations in this field may not be completed in most countries [9]. Ensuring legal effectiveness helps increase customer and investor confidence in this regard. On the other hand, there are serious uncertainties regarding crypto mining activities [10]. Anandhabalaji and Babu [11] demonstrated that to minimize this uncertainty, legal regulations must be effectively established. Otherwise, investors' uneasiness regarding this issue will increase. This situation leads to the market potential for crypto mining not being developed. In addition, Kshetri [12] concluded that legal efficiency ensures a fair competitive environment in the crypto mining industry. Thus, more investors can choose to purchase these products. Moreover, Podhorsky [13] demonstrated that legal regulations must be effectively established to protect consumer rights. In this way, investors can choose crypto products more.

Financial profitability is highly important in developing the market potential of the crypto mining industry. One of the biggest expectations of investors from financial products is financial profitability [14]. This is necessary for the sustainability of financial instruments. Otherwise, investors will not prefer these products. Potential investors give more priority to a sector that has the potential to generate profits [15]. Therefore, it is possible to attract more investments to the sector by ensuring financial profitability. Anandhabalaji et al. [16] noted that this issue contributes to the growth of the crypto mining industry. Moreover, another advantage of financial profitability is that it increases the competitiveness of crypto mining companies [17]. Companies with increased profitability can significantly increase their market share. On the other hand, Andreoulaki et al. [18] indicated that ensuring financial profitability also enables research studies on crypto mining to increase. This situation supports the development of technology on the subject.

Reducing energy costs is also necessary to improve the market potential of the crypto mining industry. One of the biggest costs of these processes is the high amount of energy consumed in this process [17]. Therefore, it is possible to increase the profit margins of mining activities by lowering energy costs. This situation allows more investors to be attracted to the sector [18]. On the other hand, Jacob et al. [19] reported that mining companies with low energy costs can gain a competitive advantage. This provides significant support to the development of the market potential of the crypto mining industry. According to Choithani et al. [20], another advantage of reducing energy costs is the environmental sustainability of the industry. With lower energy consumption, it is possible to use fewer natural resources and reduce carbon emissions. Schwiderowski et al. [21] reported that lower energy costs can encourage wider participation in the crypto mining industry. The increase in the number of investors also contributes significantly to the development of the market potential of the crypto mining industry.

As a result of the literature review, several important points can be reached. Crypto mining has several important advantages, such as increasing liquidity in the market and ensuring transaction security. Therefore, it is quite necessary to develop the market potential of the crypto mining industry. However, there are many different variables that affect this issue. This makes it difficult to determine the right action to take. On the other hand, the implementation of these actions also causes costs to increase. Therefore, implementing each of these actions is not financially feasible, as it would radically increase costs. Therefore, to use the limited budget and human resources effectively, a small number of actions that are most important must be taken. In this case, it is necessary to determine the variables that are most important for developing the market potential of the crypto mining industry. However, there are a limited number of studies have focused on this issue in the literature. This situation emerges as the most important gap in the literature. To satisfy this gap, the aim is to determine the most important criteria by establishing a new model in the literature.

3. Proposed methodology

In this proposed model, quantum theory is integrated into picture fuzzy rough sets and the M-SWARA methodology. The details of the quantum theory are presented in Equations (1)–(3) [22].

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

$$|C> = \{|u_1>, |u_2>, \ldots, |u_n>\} \tag{2}$$

$$\sum_{|u> \subseteq |C>} |Q(|u>)| = 1 \tag{3}$$

In these equations, $|u>$ gives information about an event, φ^2 represents the phase angle, and $|\varphi_1|^2$ represents the degree of belief. Picture fuzzy sets are also explained in Equations (4)–(8) [23].

$$A \subseteq B \text{ if } \mu_A(x) \leq \mu_B(x) \text{ and } n_A(x) \leq n_B(x) \text{ and } v_A(x) \geq v_B(x), \forall x \in X \tag{4}$$

$$A = B \text{ if } A \subseteq B \text{ and } B \subseteq A \tag{5}$$

$$A \cup B = \{(x, \max(\mu_A(x), \mu_B(x)), \min(n_A(x), n_B(x)), \min(v_A(x), v_B(x)))|x \in X\} \tag{6}$$

$$A \cap B = \{(x, \min(\mu_A(x), \mu_B(x)), \min(n_A(x), n_B(x)), \max(v_A(x), v_B(x)))|x \in X\} \tag{7}$$

$$coA = \overline{A} = \{(x, v_A(x), n_A(x), \mu_A(x))|x \in X\} \tag{8}$$

On the other side, the details of the fuzzy rough numbers are given below. Lower approximation $(\underline{Apr}(C_i))$, upper approximation $(\overline{Apr}(C_i))$, and boundary region $(Bnd(C_i))$ are demonstrated in Equations (9)–(11).

$$\underline{Apr}(C_i) = \cup \{Y \in X / R(Y) \leq C_i\} \tag{9}$$

$$\overline{Apr}(C_i) = \cup \{Y \in X / R(Y) \geq C_i\} \tag{10}$$

$$Bnd(C_i) = \cup \{Y \in X / R(Y) \neq C_i\} \tag{11}$$

In this scope, Y defines an arbitrary object, R represents the set of N classes $(C_1, \ldots, C_N)$. Moreover, lower limit $(\underline{Lim}(C_i))$, upper limit $(\overline{Lim}(C_i))$, and rough number $(RN(C_i))$ are given in Equations (12)–(14).

$$\underline{Lim}(C_i) = \sqrt[N_L]{\prod_{i=1}^{N_L} Y \in \underline{Apr}(C_i)} \tag{12}$$

$$\overline{Lim}(C_i) = \sqrt[N_U]{\prod_{i=1}^{N_U} Y \in \overline{Apr}(C_i)} \tag{13}$$

$$RN(C_i) = \lceil \underline{Lim}(C_i), \overline{Lim}(C_i) \rfloor \tag{14}$$

The integration of these techniques is denoted in Equation (15).

$$|C_A> = \left\{ \begin{array}{c} \langle u, (\lceil \underline{Lim}(C_{i\mu_A}), \overline{Lim}(C_{i\mu_A}) \rfloor (u), \lceil \underline{Lim}(C_{in_A}), \overline{Lim}(C_{in_A}) \rfloor (u), \\ \lceil \underline{Lim}(C_{iv_A}), \overline{Lim}(C_{iv_A}) \rfloor (u), \lceil \underline{Lim}(C_{ih_A}), \overline{Lim}(C_{ih_A}) \rfloor (u)) | u \in 2^{|C_A>} \end{array} \right\} \tag{15}$$

In this process, $C_{i\mu_A}$, C_{in_A}, C_{iv_A}, and C_{ih_A} represent the membership, neutral, non-membership, and refusal degrees, respectively. They are computed via Equations (16)–(23).

$$\underline{Lim}(C_{i\mu_A}) = \frac{1}{N_{L\mu_A}} \sum_{i=1}^{N_{L\mu_A}} Y \in \underline{Apr}(C_{i\mu_A}) \tag{16}$$

$$\underline{Lim}(C_{in_A}) = \frac{1}{N_{Ln_A}} \sum_{i=1}^{N_{Ln_A}} Y \in \underline{Apr}(C_{in_A}) \tag{17}$$

$$\underline{Lim}(C_{iv_A}) = \frac{1}{N_{Lv_A}} \sum_{i=1}^{N_{Lv_A}} Y \in \underline{Apr}(C_{iv_A}) \tag{18}$$

$$\underline{Lim}(C_{ih_A}) = \frac{1}{N_{L\pi_A}} \sum_{i=1}^{N_{L\pi_A}} Y \in \underline{Apr}(C_{ih_A}) \tag{19}$$

$$\overline{Lim}(C_{i\mu_A}) = \frac{1}{N_{U\mu_A}} \sum_{i=1}^{N_{U\mu_A}} Y \in \overline{Apr}(C_{i\mu_A}) \tag{20}$$

$$\overline{Lim}(C_{in_A}) = \frac{1}{N_{Un_A}} \sum_{i=1}^{N_{Un_A}} Y \in \overline{Apr}(C_{in_A}) \tag{21}$$

$$\overline{Lim}(C_{iv_A}) = \frac{1}{N_{Uv_A}} \sum_{i=1}^{N_{Uv_A}} Y \in \overline{Apr}(C_{iv_A}) \tag{22}$$

$$\overline{Lim}(C_{ih_A}) = \frac{1}{N_{U\pi_A}} \sum_{i=1}^{N_{U\pi_A}} Y \in \overline{Apr}(C_{ih_A}) \tag{23}$$

Within this context, $N_{L\mu_A}$, N_{Ln_A}, N_{Lv_A}, N_{Lh_A} are the number of elements in $\underline{Apr}(C_{i\mu_A})$, $\underline{Apr}(C_{in_A})$, $\underline{Apr}(C_{iv_A})$, $\underline{Apr}(C_{ih_A})$. On the other hand, $N_{U\mu_A}$, N_{Un_A}, N_{Uv_A}, N_{Uh_A} are identified for $\overline{Apr}(C_{i\mu_A})$, $\overline{Apr}(C_{in_A})$, $\overline{Apr}(C_{iv_A})$, $\overline{Apr}(C_{ih_A})$. The calculation details are given in Equations (24)–(31).

$$\underline{Apr}(C_{i\mu_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{i\mu_A}\} \tag{24}$$

$$\underline{Apr}(C_{in_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{in_A}\} \tag{25}$$

$$\underline{Apr}(C_{iv_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{iv_A}\} \tag{26}$$

$$\underline{Apr}(C_{ih_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{ih_A}\} \tag{27}$$

$$\overline{Apr}(C_{i\mu_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{i\mu_A}\} \tag{28}$$

$$\overline{Apr}(C_{in_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{in_A}\} \tag{29}$$

$$\overline{Apr}(C_{iv_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{iv_A}\} \tag{30}$$

$$\overline{Apr}(C_{ih_A}) = \cup \{Y \in X / \widetilde{R}(Y) \leq C_{ih_A}\} \tag{31}$$

Quantum picture fuzzy sets can be calculated by Equations (32) and (33).

$$C=\left[C_{\mu}.e^{j2\pi.\alpha},C_{n}.e^{j2\pi.\gamma},C_{v}.e^{j2\pi.\beta},C_{h}.e^{j2\pi.T}\right] \tag{32}$$

$$\varphi^{2}=\left|C_{\mu}(|u_{i}>)\right| \tag{33}$$

The mathematical details are given in Equations (34)–(37).

$$\lambda^{*}\widetilde{A}_{c}=\left\{\begin{array}{l}\left[\underline{Lim}(C_{\mu_{\tilde{A}}})\lambda,\overline{Lim}(C_{\mu_{\tilde{A}}})\lambda\right]e^{j2\pi.\left[\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)\lambda,\left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)\lambda\right]},\left[\underline{Lim}(C_{n_{\tilde{A}}})\lambda,\overline{Lim}(C_{n_{\tilde{A}}})\lambda\right]e^{j2\pi.\left[\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)\lambda,\left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)\lambda\right]},\\ \left[\underline{Lim}(C_{v_{\tilde{A}}})\lambda,\overline{Lim}(C_{v_{\tilde{A}}})\lambda\right]e^{j2\pi.\left[\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)\lambda,\left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)\lambda\right]},\left[\underline{Lim}(C_{h_{\tilde{A}}})\lambda,\overline{Lim}(C_{h_{\tilde{A}}})\lambda\right]e^{j2\pi.\left[\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)\lambda,\left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)\lambda\right]}\end{array}\right\},\ \lambda>0 \tag{34}$$

$$\widetilde{A}_{c}^{\ \lambda}=\left\{\begin{array}{l}\left[\underline{Lim}(C_{\mu_{\tilde{A}}})^{\lambda},\overline{Lim}(C_{\mu_{\tilde{A}}})^{\lambda}\right]e^{j2\pi.\left[\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)^{\lambda},\left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]},\left[\underline{Lim}(C_{n_{\tilde{A}}})^{\lambda},\overline{Lim}(C_{n_{\tilde{A}}})^{\lambda}\right]e^{j2\pi.\left[\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)^{\lambda},\left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]},\\ \left[\underline{Lim}(C_{v_{\tilde{A}}})^{\lambda},\overline{Lim}(C_{v_{\tilde{A}}})^{\lambda}\right]e^{j2\pi.\left[\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)^{\lambda},\left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]},\left[\underline{Lim}(C_{h_{\tilde{A}}})^{\lambda},\overline{Lim}(C_{h_{\tilde{A}}})^{\lambda}\right]e^{j2\pi.\left[\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)^{\lambda},\left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]},\end{array}\right\},\ \lambda>0 \tag{35}$$

$$\widetilde{A}_{c}\cup\widetilde{B}_{c}=\left\{\begin{array}{l}\left[min\left(\underline{Lim}(C_{\mu_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{\mu_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{B}}}{2\pi}\right)}\right),max\left(\overline{Lim}(C_{\mu_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{\mu_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{B}}}{2\pi}\right)}\right)\right],\\ \left[min\left(\underline{Lim}(C_{n_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{n_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{B}}}{2\pi}\right)}\right),max\left(\overline{Lim}(C_{n_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{n_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{B}}}{2\pi}\right)}\right)\right],\\ \left[min\left(\underline{Lim}(C_{v_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{v_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{B}}}{2\pi}\right)}\right),max\left(\overline{Lim}(C_{v_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{v_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{B}}}{2\pi}\right)}\right)\right],\\ \left[min\left(\underline{Lim}(C_{h_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{h_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{T}_{\tilde{B}}}{2\pi}\right)}\right),max\left(\overline{Lim}(C_{h_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{h_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{T}_{\tilde{B}}}{2\pi}\right)}\right)\right]\end{array}\right\} \tag{36}$$

$$\widetilde{A}_{c}\cap\widetilde{B}_{c}=\left\{\begin{array}{l}\left[max\left(\underline{Lim}(C_{\mu_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{\mu_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{B}}}{2\pi}\right)}\right),min\left(\overline{Lim}(C_{\mu_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{\mu_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{B}}}{2\pi}\right)}\right)\right],\\ \left[max\left(\underline{Lim}(C_{n_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{n_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{B}}}{2\pi}\right)}\right),min\left(\overline{Lim}(C_{n_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{n_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{B}}}{2\pi}\right)}\right)\right],\\ \left[max\left(\underline{Lim}(C_{v_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{v_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{B}}}{2\pi}\right)}\right),min\left(\overline{Lim}(C_{v_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{v_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{B}}}{2\pi}\right)}\right)\right],\\ \left[max\left(\underline{Lim}(C_{h_{\tilde{A}}})e^{j2\pi.\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)},\underline{Lim}(C_{h_{\tilde{B}}})e^{j2\pi.\left(\frac{\underline{T}_{\tilde{B}}}{2\pi}\right)}\right),min\left(\overline{Lim}(C_{h_{\tilde{A}}})e^{j2\pi.\left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)},\overline{Lim}(C_{h_{\tilde{B}}})e^{j2\pi.\left(\frac{\overline{T}_{\tilde{B}}}{2\pi}\right)}\right)\right]\end{array}\right\} \tag{37}$$

Quantum picture fuzzy tough sets are considered with the M-SWARA technique. This new methodology is created by making some adjustments to the SWARA. With the help of these new implementations, the causal directions can be identified [24]. In this process, evaluations are obtained from the experts first. By using these evaluations, a direct relation matrix is generated, as shown in Equations (38) and (39).

$$C_k = \begin{bmatrix} 0 & C_{12} & \cdots & \cdots & C_{1n} \\ C_{21} & 0 & \cdots & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & \cdots & 0 \end{bmatrix} \tag{38}$$

$$C = \begin{pmatrix} \left[min_{i=1}^{k}\left(\underline{Lim}\left(C_{\mu_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{\mu_{ij}}\right)\right)\right] e^{j2\pi.\left[min_{i=1}^{k}\left(\frac{\underline{\alpha}_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{\alpha}_{ij}}{2\pi}\right)\right]}, \\ \left[min_{i=1}^{k}\left(\underline{Lim}\left(C_{n_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{n_{ij}}\right)\right)\right] e^{j2\pi.\left[min_{i=1}^{k}\left(\frac{\underline{\gamma}_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{\gamma}_{ij}}{2\pi}\right)\right]}, \\ \left[min_{i=1}^{k}\left(\underline{Lim}\left(C_{v_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{v_{ij}}\right)\right)\right] e^{j2\pi.\left[min_{i=1}^{k}\left(\frac{\underline{\beta}_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{\beta}_{ij}}{2\pi}\right)\right]}, \\ \left[min_{i=1}^{k}\left(\underline{Lim}\left(C_{h_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{h_{ij}}\right)\right)\right] e^{j2\pi.\left[min_{i=1}^{k}\left(\frac{\underline{T}_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{T}_{ij}}{2\pi}\right)\right]} \end{pmatrix} \tag{39}$$

The defuzzified values are computed via Equation (40).

$$Defc_i = \frac{\begin{pmatrix} \underline{Lim}(C_{\mu_i}) - \underline{Lim}(C_{n_i}) + \underline{Lim}(C_{\mu_i}).(\underline{Lim}(C_{v_i}) - \underline{Lim}(C_{h_i})) + \left(\frac{\underline{\alpha}_{ij}}{2\pi}\right) - \left(\frac{\underline{\gamma}_{ij}}{2\pi}\right) + \left(\frac{\underline{\alpha}_{ij}}{2\pi}\right).\left(\left(\frac{\underline{\beta}_{ij}}{2\pi}\right) - \left(\frac{\underline{T}_{ij}}{2\pi}\right)\right) + \\ \overline{Lim}(C_{\mu_i}) - \overline{Lim}(C_{n_i}) + \overline{Lim}(C_{\mu_i}).(\overline{Lim}(C_{v_i}) - \overline{Lim}(C_{h_i})) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right) - \left(\frac{\overline{\gamma}_{ij}}{2\pi}\right) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right).\left(\left(\frac{\overline{\beta}_{ij}}{2\pi}\right) - \left(\frac{\overline{T}_{ij}}{2\pi}\right)\right) \end{pmatrix}}{2} \tag{40}$$

Finally, Equations (41)–(43) are taken into consideration to compute the significant values. They are mainly used to compute the weights and the impact relation map.

$$k_j = \begin{cases} 1, \; j = 1, \\ s_j + 1, \; j > 1 \end{cases} \tag{41}$$

$$q_j = \begin{cases} 1, \; j = 1 \\ \frac{q_{j-1}}{k_j}, \; j > 1 \end{cases} \tag{42}$$

If $s_{j-1} = s_j, q_{j-1} = q_j$; If $s_j = 0, k_{j-1} = k_j$.

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k} \tag{43}$$

4. Analysis results

The proposed decision-making approach, which is based on quantum picture fuzzy rough sets, is also applied for weighting and constructing the impact relations of the criteria. The extended M-SWARA methodology is used for applying this analysis. The details are as follows. In the first step, the set of criteria is defined for the performance determinants of the crypto mining market, as shown in Table 1.

The decision-makers use linguistic choices, and quantum picture fuzzy numbers are assigned according to the scales in Table 2.

The linguistic results and their fuzzy numbers are given in Tables 3 and 4, respectively.

The following step illustrates the quantum picture fuzzy rough sets for the relation matrix, as shown in Table 5.

The normalized values are computed by using the defuzzified values of the fuzzy sets, and the results are given in Table 6.

The s_j, k_j, q_j, and w_j values of the relation matrix are computed in Table 7.

The following step shows the results of the relation and stable matrices with the impact-relations, as shown in Tables 8 and 9.

The results show that minimizing energy expenses (C1) is the most important determinant, whereas financial profitability (C2) has the least importance. Similarly, technological improvement (C4) is the second most significant item in this framework. However, minimizing energy expenses (C1) is the most influential determinant among the criteria set.

Table 1
Selected criteria set for the performance determinants.

Criteria	Code
Minimizing energy expenses	C1
Financial profitability	C2
Effective legal regulations	C3
Technological improvements	C4

Table 2
Linguistic scales and quantum picture fuzzy numbers for evaluation.

Scale for criteria	Scale for alternative	Degree	Fuzzy set
No (n)	Weakest (w)	0.40	$\begin{bmatrix} \sqrt{0.16}e^{j2\pi.0.4}, \\ \sqrt{0.10}e^{j2\pi.0.25}, \\ \sqrt{0.46}e^{j2\pi.0.22}, \\ \sqrt{0.28}e^{j2\pi.0.13} \end{bmatrix}$
Some (s)	Poor (p)	0.45	$\begin{bmatrix} \sqrt{0.20}e^{j2\pi.0.45}, \\ \sqrt{0.13}e^{j2\pi.0.28}, \\ \sqrt{0.42}e^{j2\pi.0.17}, \\ \sqrt{0.25}e^{j2\pi.0.10} \end{bmatrix}$
Medium (m)	Fair (f)	0.50	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$
High (h)	Good (g)	0.55	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi.0.55}, \\ \sqrt{0.19}e^{j2\pi.0.34}, \\ \sqrt{0.32}e^{j2\pi.0.07}, \\ \sqrt{0.19}e^{j2\pi.0.04} \end{bmatrix}$
Very high (vh)	Best (b)	0.60	$\begin{bmatrix} \sqrt{0.36}e^{j2\pi.0.6}, \\ \sqrt{0.22}e^{j2\pi.0.37}, \\ \sqrt{0.26}e^{j2\pi.0.02}, \\ \sqrt{0.16}e^{j2\pi.0.01} \end{bmatrix}$

Table 3
Linguistic evaluations of decision-makers for the criteria.

Expert 1				
	C1	C2	C3	C4
C1		S	H	H
C2	M		S	S
C3	H	S		M
C4	M	S	M	
Expert 2				
	C1	**C2**	**C3**	**C4**
C1		S	H	H
C2	M		S	M
C3	H	M		M
C4	H	S	M	
Expert 3				
	C1	**C2**	**C3**	**C4**
C1		M	H	VH
C2	M		M	M
C3	VH	M		H
C4	M	M	M	

Additionally, minimizing energy expenses (C1) has an impact on technological improvements (C4) only.

5. Discussion

Reducing energy costs has emerged as the most important factor for improving the market potential of the crypto mining industry. One of the most important costs in the crypto mining process is the cost of energy. It is possible to talk about the many disadvantages of this situation. First, excessive energy consumption causes natural resources to be consumed faster. This situation significantly threatens environmental sustainability. Similarly, Kräussl and Tugnetti [25] discussed that obtaining the energy used in crypto mining from fossil fuels also poses some problems. In this case, a significant amount of carbon gas is released into the atmosphere. This situation affects the health of living things very negatively. Jayabalasamy et al. [26] stated that due to these problems, it is important to reduce energy costs in crypto mining. In this way, businesses can gain a significant competitive advantage. Thus, the market shares of businesses in the crypto mining market can increase significantly. On the other hand, Bâra et al. [27] emphasized that low energy costs also allow the profitability of projects to increase. Ensuring the financial profitability of projects also supports their long-term sustainability [31–33].

Technological developments also play an important role in developing the market potential of the crypto mining industry. Owing to new technologies, more efficient mining equipment can be used. In this way, it is possible to consume less energy during the mining process. This also contributes to increasing the financial profitability of the projects. According to Deepak et al. [28], this situation can help more investors choose these products. Technological advances also support taking the necessary security measures in mining processes. Since crypto mining is a very new application, investors may have some concerns. Cai et al. [29] emphasized that this contributes to increasing confidence in these financial products. In this way, it is possible for more investors to choose these products. On the other hand, Porfirenko et al. [30] discussed that some other studies also emphasize that the financial performance of crypto mining is important. In this context, it is underlined that the profitability of projects must be increased to ensure their long-term sustainability.

6. Conclusion

This study aims to understand the main indicators to improve the market potential of crypto mining activities. A new model has been constructed to achieve this objective. The selected criteria of the market potential of crypto mining are weighted by using quantum picture fuzzy rough set-based M-SWARA. The findings demonstrate that reducing energy costs is the most important factor for improving the market potential of the crypto mining industry. Furthermore, technological developments also play an important role in this regard. Additionally, minimizing energy expenses is the most influential determinant among the criteria set. Additionally, minimizing energy expenses has an impact on technological improvements only.

The main contribution of this study is the generation of a new decision-making model to understand the key issues related to the market potential of crypto mining activities. The M-SWARA model is taken into consideration for criteria weighting. Owing to this issue, the causal relationships between the items can be identified. The main theoretical limitation of this study is that only the subject of market potential is taken into consideration. However, there are also several other key issues for crypto mining activities, such as risk management and operational efficiency. These subjects can be evaluated in future studies. The proposed model also has several key limitations. For example, the significance weights of the experts are not identified in this model. Nevertheless, these people can have different characteristics. Thus, for future studies, artificial intelligence techniques can be used in the decision-making process to compute the weights of experts.

Table 4
Quantum picture fuzzy numbers for the relation matrix.

Expert 1	C1	C2	C3	C4
C1		$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
C2	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$
C3	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$
C4	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	

Expert 2	C1	C2	C3	C4
C1		$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
C2	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$
C3	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$
C4	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	

Expert 3	C1	C2	C3	C4
C1		$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$
C2	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$
C3	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$		$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
C4	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	

Table 5
Quantum picture fuzzy rough sets for the relation matrix.

	C1	C2	C3	C4
C1		$\lceil\sqrt{0.20},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.45,0.50\rfloor}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rfloor\ e^{j2\pi.\lceil 0.28,0.31\rfloor}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rfloor\ e^{j2\pi.\lceil 0.12,0.17\rfloor}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.07,0.10\rfloor}$	$\lceil\sqrt{0.25},\sqrt{0.30}\rfloor\ e^{j2\pi.\lceil 0.50,0.55\rfloor}$, $\lceil\sqrt{0.15},\sqrt{0.19}\rfloor\ e^{j2\pi.\lceil 0.31,0.34\rfloor}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rfloor\ e^{j2\pi.\lceil 0.07,0.12\rfloor}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rfloor\ e^{j2\pi.\lceil 0.04,0.07\rfloor}$	$\lceil\sqrt{0.25},\sqrt{0.36}\rfloor\ e^{j2\pi.\lceil 0.50,0.60\rfloor}$, $\lceil\sqrt{0.15},\sqrt{0.22}\rfloor\ e^{j2\pi.\lceil 0.31,0.37\rfloor}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rfloor\ e^{j2\pi.\lceil 0.07,0.12\rfloor}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rfloor\ e^{j2\pi.\lceil 0.04,0.07\rfloor}$
C2	$\lceil\sqrt{0.25},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.50,0.50\rfloor}$, $\lceil\sqrt{0.15},\sqrt{0.15}\rfloor\ e^{j2\pi.\lceil 0.31,0.31\rfloor}$, $\lceil\sqrt{0.32},\sqrt{0.32}\rfloor\ e^{j2\pi.\lceil 0.07,0.07\rfloor}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rfloor\ e^{j2\pi.\lceil 0.04,0.04\rfloor}$		$\lceil\sqrt{0.20},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.45,0.50\rfloor}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rfloor\ e^{j2\pi.\lceil 0.28,0.31\rfloor}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rfloor\ e^{j2\pi.\lceil 0.12,0.17\rfloor}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.07,0.10\rfloor}$	$\lceil\sqrt{0.20},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.45,0.50\rfloor}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rfloor\ e^{j2\pi.\lceil 0.28,0.31\rfloor}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rfloor\ e^{j2\pi.\lceil 0.12,0.17\rfloor}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.07,0.10\rfloor}$
C3	$\lceil\sqrt{0.25},\sqrt{0.36}\rfloor\ e^{j2\pi.\lceil 0.50,0.60\rfloor}$, $\lceil\sqrt{0.15},\sqrt{0.22}\rfloor\ e^{j2\pi.\lceil 0.31,0.37\rfloor}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rfloor\ e^{j2\pi.\lceil 0.07,0.12\rfloor}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rfloor\ e^{j2\pi.\lceil 0.04,0.07\rfloor}$	$\lceil\sqrt{0.20},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.45,0.50\rfloor}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rfloor\ e^{j2\pi.\lceil 0.28,0.31\rfloor}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rfloor\ e^{j2\pi.\lceil 0.12,0.17\rfloor}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.07,0.10\rfloor}$		$\lceil\sqrt{0.16},\sqrt{0.30}\rfloor\ e^{j2\pi.\lceil 0.40,0.55\rfloor}$, $\lceil\sqrt{0.10},\sqrt{0.19}\rfloor\ e^{j2\pi.\lceil 0.25,0.34\rfloor}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rfloor\ e^{j2\pi.\lceil 0.07,0.12\rfloor}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rfloor\ e^{j2\pi.\lceil 0.04,0.07\rfloor}$
C4	$\lceil\sqrt{0.20},\sqrt{0.30}\rfloor\ e^{j2\pi.\lceil 0.45,0.55\rfloor}$, $\lceil\sqrt{0.13},\sqrt{0.19}\rfloor\ e^{j2\pi.\lceil 0.28,0.34\rfloor}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rfloor\ e^{j2\pi.\lceil 0.07,0.17\rfloor}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.04,0.10\rfloor}$	$\lceil\sqrt{0.20},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.45,0.50\rfloor}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rfloor\ e^{j2\pi.\lceil 0.28,0.31\rfloor}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rfloor\ e^{j2\pi.\lceil 0.12,0.17\rfloor}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.07,0.10\rfloor}$	$\lceil\sqrt{0.25},\sqrt{0.25}\rfloor\ e^{j2\pi.\lceil 0.50,0.50\rfloor}$, $\lceil\sqrt{0.15},\sqrt{0.15}\rfloor\ e^{j2\pi.\lceil 0.31,0.31\rfloor}$, $\lceil\sqrt{0.32},\sqrt{0.32}\rfloor\ e^{j2\pi.\lceil 0.07,0.07\rfloor}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rfloor\ e^{j2\pi.\lceil 0.04,0.04\rfloor}$	

Table 6
The normalized matrix.

	C1	C2	C3	C4
C1	0.000	0.311	0.341	0.348
C2	0.343	0.000	0.329	0.329
C3	0.357	0.319	0.000	0.324
C4	0.342	0.322	0.336	0.000

Table 7
The s_j, k_j, q_j, and w_j values.

C1	s_j	k_j	q_j	w_j	C2	s_j	k_j	q_j	w_j
C4	0.348	1.000	1.000	0.432	C1	0.343	1.000	1.000	0.399
C3	0.341	1.341	0.746	0.322	C3	0.329	1.329	0.753	0.300
C2	0.311	1.311	0.569	0.246	C4	0.329	1.000	0.753	0.300
C3	s_j	k_j	q_j	w_j	**C4**	s_j	k_j	q_j	w_j
C1	0.357	1.000	1.000	0.430	C1	0.342	1.000	1.000	0.432
C4	0.324	1.324	0.755	0.324	C3	0.336	1.336	0.748	0.323
C2	0.319	1.319	0.573	0.246	C2	0.322	1.322	0.566	0.245

Table 8
Relation matrix.

	C1	C2	C3	C4
C1		0.246	0.322	0.432
C2	0.399		0.300	0.300
C3	0.430	0.246		0.324
C4	0.432	0.245	0.323	

Table 9
Stable matrix.

	C1	C2	C3	C4	Impact-relations
C1	0.297	0.297	0.297	0.297	C1→C4
C2	0.197	0.197	0.197	0.197	C2→C1
C3	0.241	0.241	0.241	0.241	C3→C1
C4	0.265	0.265	0.265	0.265	C4→C1

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Hasan Dincer: Conceptualization. **Serhat Yüksel:** Data curation. **Gabor Pinter:** Formal analysis. **Alexey Mikhaylov:** Writing – original draft.

References

[1] A. Bhatt, W. Ongsakul, N. Madhu M, et al., Optimal energy management system for carbon–neutral microgrid integrating second-life batteries and crypto mining devices, Sustain. Energy Technol. Assessments 64 (2024) 103686, https://doi.org/10.1016/j.seta.2024.103686.

[2] A. Lal, H. Niaz, J.J. Liu, et al., Can Bitcoin mining empower energy transition and fuel sustainable development goals in the US? J. Clean. Prod. 439 (2024) 140799 https://doi.org/10.1016/j.jclepro.2024.140799.

[3] I. Yousaf, A. Abrar, U. Bin Yousaf, et al., Environmental attention and uncertainties of cryptocurrency market: examining linkages with crypto-mining stocks, Finance Res. Lett. 59 (2024) 104672, https://doi.org/10.1016/j.frl.2023.104672.

[4] M.A. Ehyaei, F. Esmaeilion, M. Shamoushaki, et al., The feasibility study of the production of Bitcoin with geothermal energy: case study, Energy Sci. Eng. 12 (3) (2024) 755–770, https://doi.org/10.1002/ese3.1648.

[5] A. Rosales, H. Millar, A. Richardson, Leveraging intra-provincial regulatory differences in a post-Paris context: cryptocurrency mining “reverse battery” strategy in Atlantic Canada, Extr. Ind. Soc. 17 (2024) 101396, https://doi.org/10.1016/j.exis.2023.101396.

[6] V. Manahov, The great crypto crash in September 2018: why did the cryptocurrency market collapse? Ann. Oper. Res. 332 (1) (2024) 579–616, https://doi.org/10.1007/s10479-023-05575-0.

[7] H. Estecahandy, Geopolitics of cryptocurrency mining in Kazakhstan, Cent. Asian Surv. (2024) 1–19, https://doi.org/10.1080/02634937.2024.2324192.
[8] H. Yu, Y. Sun, Y. Liu, et al., Bitcoin gold, Litecoin silver: an introduction to cryptocurrency valuation and trading strategy, in: K. Arai (Ed.), Advances in Information and Communication, Springer, Cham, 2024, pp. 73–586, https://doi.org/10.1007/978-3-031-54053-0_39.
[9] M. Onifade, J.A. Adebisi, T. Zvarivadza, Recent advances in blockchain technology: prospects, applications and constraints in the minerals industry, Int. J. Min. Reclamat. Environ. 38 (7) (2024) 497–533, https://doi.org/10.1080/17480930.2024.2319453.
[10] A. Mercik, T. Słoński, M. Karaś, Understanding crypto-asset exposure: an investigation of its impact on performance and stock sensitivity among listed companies, Int. Rev. Financ. Anal. 92 (2024) 103070, https://doi.org/10.1016/j.irfa.2024.103070.
[11] V. Anandhabalaji, M. Babu, Research trends in energy consumption within the cryptocurrency ecosystem, in: Proceedings of the 2024 Second International Conference on Smart Technologies for Power and Renewable Energy (SPECon), IEEE, 2024, pp. 1–8, https://doi.org/10.1109/SPECon61254.2024.10537587.
[12] N. Kshetri, Editorial: economic, social and political impacts of blockchain, Telecommun. Pol. 48 (3) (2024) 102718, https://doi.org/10.1016/j.telpol.2024.102718.
[13] A. Podhorsky, Bursting the Bitcoin bubble: do market prices reflect fundamental Bitcoin value? Int. Rev. Financ. Anal. 93 (2024) 103158 https://doi.org/10.1016/j.irfa.2024.103158.
[14] C. Wronka, Crypto-asset activities and markets in the European Union: issues, challenges and considerations for regulation, supervision and oversight, J. Bank. Regul. 25 (1) (2024) 84–93, https://doi.org/10.1057/s41261-023-00217-8.
[15] X. Wang, J. Liu, Q. Xie, Quantile frequency connectedness between energy tokens, crypto market, and renewable energy stock markets, Heliyon 10 (3) (2024) e25068, https://doi.org/10.1016/j.heliyon.2024.e25068.
[16] V. Anandhabalaji, M. Babu, R. Brintha, Energy consumption by cryptocurrency: a bibliometric analysis revealing research trends and insights, Energy Nexus 13 (2024) 100274, https://doi.org/10.1016/j.nexus.2024.100274.
[17] P. Radanliev, The rise and fall of cryptocurrencies: defining the economic and social values of blockchain technologies, assessing the opportunities, and defining the financial and cybersecurity risks of the metaverse, Financ. Innov. 10 (2024) 1, https://doi.org/10.1186/s40854-023-00537-8.
[18] I. Andreoulaki, A. Papapostolou, V. Marinakis, Evaluating the barriers to blockchain adoption in the energy sector: a multicriteria approach using the analytical hierarchy process for group decision making, Energies 17 (6) (2024) 1278, https://doi.org/10.3390/en17061278.
[19] V.S. Jacob, S.P. Mishra, S. Radhakrishnan, Is decentralization sustainable in the Bitcoin system? Decis. Support Syst. 180 (2024) 114178 https://doi.org/10.1016/j.dss.2024.114178.
[20] T. Choithani, A. Chowdhury, S. Patel, et al., A comprehensive study of artificial intelligence and cybersecurity on Bitcoin, crypto currency and banking system, Ann Data Sci (2022) 1–33.
[21] J. Schwiderowski, A.B. Pedersen, R. Beck, Crypto tokens and token systems, Inf. Syst. Front 26 (1) (2024) 319–332, https://doi.org/10.1007/s10796-023-10382-w.
[22] G. Kou, D. Pamucar, H. Dinçer, et al., An integrated quantum picture fuzzy rough sets with golden cuts for evaluating carbon footprint-based investment decision policies of sustainable industries, Appl. Soft Comput. 155 (2024) 111428, https://doi.org/10.1016/j.asoc.2024.111428.
[23] H. Dinçer, S. Yüksel, B. Abadi, et al., Development of wind energy in the agricultural sector of Iran and investment priorities of the decision maker groups using artificial intelligence-based quantum hybrid picture fuzzy rough modelling, in: Proceedings of the 2024 IEEE 8th Energy Conference (ENERGYCON), IEEE, 2024, pp. 1–5, https://doi.org/10.1109/ENERGYCON58629.2024.10488816.
[24] A.F. Aysan, S. Yüksel, S. Eti, et al., A unified theory of acceptance and use of technology and fuzzy artificial intelligence model for electric vehicle demand analysis, Decis. Anal. J. 11 (2024) 100455, https://doi.org/10.1016/j.dajour.2024.100455.
[25] R. Kräussl, A. Tugnetti, Non-fungible tokens (NFTs): a review of pricing determinants, applications and opportunities, J. Econ. Surv. 38 (2) (2024) 555–574, https://doi.org/10.1111/joes.12597.
[26] G. Jayabalasamy, C. Pujol, K. Latha Bhaskaran, Application of graph theory for blockchain technologies, Mathematics 12 (8) (2024) 1133, https://doi.org/10.3390/math12081133.
[27] A. Bâra, S.V. Oprea, M. Panait, Insights into Bitcoin and energy nexus. A Bitcoin price prediction in bull and bear markets using a complex meta model and SQL analytical functions, Appl. Intell. 54 (8) (2024) 5996–6024, https://doi.org/10.1007/s10489-024-05474-2.
[28] P. Gulia Deepak, N.S. Gill, et al., Exploring the potential of blockchain technology in an IoT-enabled environment: a review, IEEE Access 12 (2024) 31197–31227, https://doi.org/10.1109/ACCESS.2024.3366656.
[29] C.W. Cai, R. Xue, B. Zhou, Cryptocurrency puzzles: acomprehensive review and re-introduction, J. Account. Lit. 46 (1) (2024) 26–50, https://doi.org/10.1108/jal-02-2023-0023.
[30] V. Porfirenko, M. Melnyk, V. Ivanov, et al., Organization and features of investing in the cryptocurrency market in Ukraine, in: R.E. Khoury, N. Nasrallah (Eds.), Intelligent Systems, Business, and Innovation Research, Springer, Cham, 2024, pp. 213–225, https://doi.org/10.1007/978-3-031-36895-0_18.
[31] J. An, A. Mikhaylov, S-U. Jung, The strategy of South Korea in the global oil market, Energies 13 (10) (2020) 2491. https://doi.org/10.3390/en13102491.
[32] A. Mikhaylov, Understanding the risks associated with wallets, depository services, trading, lending, and borrowing in the crypto space, J. Infrastruct. Policy Dev. 7 (3) (2023) 2223. https://doi.org/10.24294/jipd.v7i3.2223.
[33] A. Mikhaylov, H. Dinçer, S. Yüksel, Bitcoin mempool growth and trading volumes: Integrated approach based on QROF Multi-SWARA and aggregation operators, J. Innov. Knowl. 8 (3) (2023) 100378. https://doi.org/10.1016/j.jik.2023.100378.