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Improving sustainability in the tourism industry through blockchain technology: Challenges and opportunities

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ABSTRACT

The tourism industry is extremely important to the world economy; yet, the industry falls short when it comes to economic, social, and environmental issues. Blockchain as an information technology can be utilized to help solve these issues and establish sustainable tourism globally. However, the challenges to blockchain adoption in the tourism industry have not yet been examined systematically. The goal of this study, therefore, is three-fold: we first identify the challenges to blockchain using literature review and expert opinions. Then, we examine them using the proposed rough Interpretive Structural Modeling - Cross-Impact Matrix Multiplication based on expert judgments. Finally, we link these challenges to diffusion of innovation theory. The results suggest that “lack of technical maturity” and “lack of interoperability” are the most important challenges of blockchain in the tourism industry. The findings of the study support macro- and micro-level decision-making in tourism industry’s prospective applications of blockchain.

1. Introduction

Tourism accounted for 5.5 percent of global GDP and 272 million jobs, making it one of the most important industries in the world in 2019 (World Travel & Tourism Council, 2021). Prior to the COVID-19 pandemic, one out of every four new jobs produced over a five-year period was in the tourism industry. In 2019, for example, the industry grew at a rate of 3.5 percent, outpacing the global economy for the ninth year in a row.

However, despite the industry’s positive impact, there are still concerns about its potentially harmful effects on both local people and the environment. Travelers consume more water, food, and energy, thus generating more waste than they do at home, putting a strain on some of the world’s most vulnerable and/or impoverished locations (Misrahi et al., 2021). To address these problems, sustainability is increasingly being considered as a strategic enabler for the tourism industry (Dwyer, 2005; Rosato et al., 2021; Wu et al., 2019). To ensure long-term sustainability in tourism industry, a sufficient balance must be struck between these dimensions. To tackle the issue of sustainable tourism industry, a shift in incentives in favor of protecting and repairing natural systems, as well as a dramatic reorganization of technological, economic, and social systems is required (WTTC & Harward., 2021).

Hall, Gossling, and Scott (2015) suggest that the challenges to sustainable tourism can be approached in a number of different ways. For example, information technologies in general can efficiently be employed to address economic, societal, and environmental issues (Ali, Rasoolimanesh, & Cobanoglu, 2020; Bolici, Acciarini, Marchegiani, & Pirolo, 2020; Buhalis et al., 2019; Herrera-Cano (MIB) C. and Herrera-Cano (2016); Zsarnoczky, 2018). Among several information technologies, blockchain is capable of supporting efforts to improve sustainability in tourism (Erceg, Damoska Sekuloska, & Kelić, 2020; Rejeb and Rejeb, 2019; Tyan et al., 2020). Boucher, Nascimento, and Kritikos (2017) argue that blockchain applications can support tourism supply chains while also supporting interactions with external

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stakeholders. The tourism industry is connected to many other industries in the world economy, and it plays a significant role in enhancing world economies; however, tourism may lead to economic, social, and environmental issues. Blockchain as an information technology can be utilized to help solve these issues and can aid in enhancing the sustainability of tourism industry. Blockchain, which is a distributed database that keeps a list of data records secured from tampering and alteration, can guarantee that the information is reliable and valid. Note that this is highly critical in building sustainability in tourism. Furthermore, blockchain has recently attracted a lot of attention from both practitioners and academics due to its effective platforms to streamline industries (Rejeb & Rejeb, 2019).

Although investigations into the difficulties of implementing blockchain have been emerging, the extant studies have highlighted several barriers to blockchain adoption despite blockchain's perceived potential capabilities by stakeholders (Toufaily et al., 2021). Some of those studies are country- and industry-specific (Sydow et al., 2020), while others are generic (Toufaily et al., 2021). However, no empirical study has yet been conducted on the challenges of adopting blockchain to enhance sustainability in the tourism industry.

Therefore, the main goal of this study is to examine the blockchain adoption challenges toward improving sustainability in the tourism industry through expert opinions. To achieve the goal of the study, our research methodology principally employs two-step research process. First, the list of challenges to blockchain adoption in tourism industry was specified through literature review. Second, the list of challenges was finalized by expert opinions. Third, a quantitative decision framework based on rough Interpretive Structural Modeling (ISM)- Cross-Impact Matrix Multiplication (MICMAC) is proposed to examine the associations among the challenges. Finally, the diffusion of blockchain in the tourism industry (Bolici et al., 2020; Grover, Kar, & Janssen, 2019) is investigated by using the diffusion of innovation (DOI) theory (Rogers, 1963). More specifically, in this study, the challenges of blockchain adoption were also assigned to the theory of DOI to explain the adoption stages of blockchain in the tourism industry. The following research questions (*RQs*) are specifically addressed:

RQ1. What are the challenges of blockchain adoption to improve sustainability in the tourism industry?

RQ2. What are the associations between the challenges of adopting blockchain to improve sustainability in the tourism industry?

RQ3. How are the challenges linked to the innovation-decision process of DOI?

The findings of this study contribute to the existing literature as follows: first, to the best of our knowledge, this research is a first attempt to identify the driving and dependency powers of the challenges to blockchain adoption towards improving sustainability in tourism industry. Second, since there are only a few studies on blockchain diffusion, this research links the blockchain adoption challenges with the innovation-decision process of DOI to identify the relevant stages of blockchain adoption in the tourism industry. The contributions of this study are further discussed in detail along with the managerial and policy implications of the findings.

In the context of multi-criteria decision-making, decision makers can usually assess the link between factors using two different techniques. For example, Decision making trial and evaluation laboratory (DEMATEL) suggests that only one of the two variables affects the other and assumes the inter-variable relationship as one-way (Kumar and Dixit, 2018). Although the scale and several extensions to DEMATEL improve its robustness, that one-way view of assuming inter-variable link is contemplated as a limitation. The proposed rough ISM-MICMAC, on the other hand, articulates the relationships between factors as an interval using rough numbers. As a result, in the interval form, the connection evaluation swings away from certainty and approaches toward trueness. Furthermore, because the assessment intervals are derived from expert judgments, the analyses' reliability improves. Hence, we argue that the proposed rough-ISM-MICMAC model ensures more dependability, impartiality, and coherence.

2. Background

2.1. Sustainability in tourism industry

Setting out priorities for sustainable development in the 21st century, Agenda 21 "recognized tourism as a model form of economic development that should improve the quality of life of the host community, provide a high quality of experience for the visitor, and maintain the quality of the environment on which both the host community and the visitor depend" (WTO, 2005). Governments and the global tourism industry may implement a number of initiatives and goals identified by Agenda 21. These encompass enhanced institutional collaboration, water waste management, educating and training minorities, and exchanging knowledge, expertise, and technology associated with travel and tourism (Liburd and Edwards, 2010). With a growing awareness of the need for sustainability in tourism industries, ecotourism also serves as a remedy for mitigating harmful effects through environmentally beneficial activities (Li et al., 2021). With that in mind, ecotourism is defined by the use of the fewest resources, as it meets the requirement for clean air and water while also allowing people to engage themselves in nature (Hasana, Swain, & George, 2022).

Moreover, the World Trade Organization (WTO, 2005) argued that "sustainable tourism should: (1) make optimal use of environmental resources that constitute a key element in tourism development by maintaining essential ecological processes and helping to conserve natural heritage and biodiversity, (2) respect the socio-cultural authenticity of host communities, conserve their built and living cultural heritage and traditional values, and contribute to inter-cultural understanding and tolerance, and (3) ensure viable, long-term economic operations by providing socio-economic benefits to all stakeholders that are fairly distributed, including stable employment and income-earning opportunities and social services to host communities, and contributing to poverty alleviation".

There are many studies regarding sustainability in tourism industry. To name a few, McCool (2016) comprehensively discussed the changing meanings of sustainable tourism. The author suggested that the conventional paradigm of sustainable tourism is grounded in the association of what is environmentally suitable, socially and culturally proper, and economically achievable, which has become the norm for implementing sustainability in the tourism industry across the globe. He concludes that more studies are needed to indicate how sustainability in the tourism industry is ensured and operationalized. In another study, Fayos-Solà and Cooper (2019) argued that reform, re-engineering, and disruptive innovation will be required if civilization is to face the major difficulties of the twenty-first century. They also contend that information and communication technologies will transform the tourism operations. Robaina and Madaleno (2019) claimed that tourism can put a strain on natural resources such as energy, food, raw materials, land, water, and marine resources in terms of availability and pricing.. The concept of eco-efficiency is therefore critical to the sustainability of the tourism industry. Eco-efficiency comprises reorienting tourism operations in a circular economy (CE) setting to use fewer resources and have a lower environmental effect. Yu and Duverger (2019) argued that, even if technology innovation has been the influential force behind shifting business paradigm, major changes in the economy and society require the support of a legislative and regulatory framework as well as business ethics. Thus, to enable sustainability in tourism, both public policymakers and private businesses must be adaptable to new technology development and market change. Lastly, Rodríguez, Florido, and Jacob (2020) examined CE in the context of tourism and identified current research opportunities. Their findings indicate that more research is needed to improve circularity that generates alternative means to build more sustainability in tourism industry.

2.2. Blockchain and sustainability in the tourism industry

Blockchain is a peer-to-peer system that is expected to disrupt many industries (e.g., energy, logistics, health, food, agriculture, finance, government, tourism) in the next decade (Ante, Steinmetz, & Fiedler, 2021; Ar et al., 2020; Ar, Erol, & Ozdemir, 2018; Erol et al., 2020; Erol et al., 2022 (a); Erol et al., 2022 (b); Lim et al., 2021; Nandi et al., 2020; Nuryyev et al., 2020; Önder & Treiblmaier, 2018; Ozdemir et al., 2021; Ozdemir et al., 2020; Sanka et al., 2021) by building trust among the companies. Blockchain is a secure, decentralized public ledger in which each member of a network can view their transaction history, eliminating the necessity for a third party (Pilkington, 2016). Each block in the chain represents a network member's acknowledgement that a transaction took place and was not tampered with. Furthermore, each block comprises information from the preceding block, which builds a sequence of blocks in a timely manner (Nakamoto, 2008).

A growing body of literature has elaborated on the features of blockchain, which could potentially improve sustainability in the tourism industry. For example, Kwok and Koh (2019) reviewed the prospects that small island economies have in adopting blockchain technology, as well as the practical consequences for tourist stakeholders. They suggested that reservation and ticketing, credential management, digital payment, and identity management are key blockchain applications in tourism industry. The authors concluded that empirical studies are needed to demonstrate the true potential of blockchain in the tourism industry. Baralla, Pinna, Tonelli, Marchesi, and Mannaro (2019) developed a blockchain-based system to help tourism services and activities, as well as to support local agri-food products. Rejeb and Rejeb (2019) further argued that blockchain could change the course of action in tourism through enhanced trust, disintermediation, loyalty programs, and effective food tracking. Also, Önder and Gunter (2020) showed that blockchain can be used in the tourism industry for loyalty programs, luggage tracking, smart contracting and, food traceability, and authenticity. Conducting a content analysis of 175 studies on blockchain and tourism, Thees et al. (2020) postulated that blockchain can create value through planning itineraries, interacting directly, connecting cars, managing hotel capacities, and tracking food. In another study, Treiblmaier (2021) argued that blockchain research should focus on tokens, which is highly significant for comprehending the viewpoint of travelers. The author also argued that tokens signify value and are expected to create the token economy in near future.

Furthermore, Willie (2019), Treiblmaier (2020), Kizildag et al. (2020), Yadav et al. (2021), Irannezhad and Mahadevan (2021), and Nam et al. (2021) argued that blockchain may be used in various operations of the tourism industry, such as "inventory management," "maintenance and tracking," "content, reservations and ticketing," "payments and tax compliance," "loyalty programs," "tokenization," "identity and credential management," "baggage tracking," "smart contracting," "cooperation and coopetition," "food authenticity," "supply chain traceability,", "waste management", and "disintermediation." In a similar vein, Filimonau and Naumova (2020) assessed the scope of possible blockchain integration into hospitality operations. After reviewing the current implementation of blockchain in the tourism industry, the authors suggested that blockchain could boost sustainability through better traceability, enhanced sharing economy, improved authenticity, and audibility. Rashideh (2020) discussed blockchain platforms in the tourism industry, including LockChain, Beetoken/Beenest, Winding Tree, ShoCard&SITA, Trippki, and TUI-bed-SWAP, which are used for renting out property, home-sharing, baggage tracking, identity management, customer loyalty, and inventory management. The author concluded that sustainability in tourism supply chain could be improved by the removal of intermediaries. Tyan et al. (2021) also examined how blockchain may help to promote sustainable tourism and concluded that blockchain has the ability to help to sustainable tourism development through enhancing the local economy, regulating the food supply chain and minimizing food waste, achieving tourist satisfaction, influencing tourists' sustainable behavior, and addressing awareness concerns. Luo and Zhou (2021) developed a blockchain-based platform or smart tourism, which connects the company and customers to increase the efficiency of the tourism supply chain. Hence, financial and social sustainability through enhanced customer satisfaction is achieved. Lastly, Demirel, Karagöz Zeren, and Hakan (2021) built a blockchain architecture with a smart contract that provides some value added in terms of adaptability. They argued that smart contract implementations are beneficial to satisfy consumers' expectations for hygiene and health standards, which improve social sustainability performance of the tourism supply chain.

Although adopting blockchain technology has tremendous potential for sustainable tourism development, the extant studies collectively suggest that to discover the extent to which blockchain can realize its promise and how the tourism industry could benefit from its adoption, more empirical research is required (Kwok and Koh, 2019; Treiblmaier and Önder, 2019; Yadav et al., 2021).

2.3. Challenges to blockchain adoption

In this section, the literature was reviewed on the challenges to blockchain adoption comprehensively. Databases including Science Direct, Taylor & Francis, SCOPUS, Web of Science, EBSCO, Emerald, and Springer were used to conduct the search. The following keywords were employed: "barriers to blockchain adoption," "challenges of blockchain adoption," and "challenges of blockchain adoption in sustainability." The literature review is limited to peer-reviewed research articles and covers studies published in English. Theses and dissertations were excluded. Despite blockchain's strength to improve industries, only several studies have scrutinized the challenges of blockchain adoption. Our review resulted in 21 papers as displayed in Table 1.

The literature review suggests that there are several studies on the challenges to blockchain adoption. While some of these studies are industry specific, the rest are generic. In addition, the authors use both qualitative and quantitative techniques when they identify the challenges. Note that only a few study focuses on the associations among the challenges. Our comprehensive literature review also suggests that no prior study has empirically and/or quantitatively examined the blockchain adoption challenges to improve the sustainability performance of the tourism industry.

2.4. Linking blockchain adoption challenges to the theory of diffusion of innovation

Adoption of blockchain can be explained by diffusion of innovation (DOI) theory (Rogers, 1963): "Innovation diffusion models are useful for the analysis of both the timing of the diffusion of an innovation inside a given population and of the dynamic of the same adoption pattern across different adopters' populations" (Scaglione, 2020, p. 1). Previously, this theory has been applied to the tourism industry and its acceptance of various technologies. Some examples include the adoption of renewable energy in the hospitality sector (Dhirasasna, Becken, & Sahin, 2020), Brazil's adoption of solar energy by residential customers (dos Santos et al., 2018), the acceptance of the Uber mobile application by consumers (Min et al., 2019), and ethical tourist behavior innovation (Ganglmair-Wooliscroft & Wooliscroft, 2016).

An innovation can be any idea, product, or practice that is perceived as new by society. Blockchain is still nascent in terms of adoption by various industries (Biswas & Gupta, 2019; Janssen, Weerakkody, Ismagilova, Sivarajah, & Irani, 2020). With that in mind, we argue that it would be beneficial to examine blockchain adoption through the theory of DOI in the tourism industry. The main idea of the theory is to explain how, over time, an innovation is spread among the social system. The

Table 1
Literature on challenges of blockchain adoption.

Paper	Method	Industry	Country	Main Findings
Toufaily et al. (2021)	Exploratory study using semi-structured interviews	Not specified	Middle East and North African Region	Public and private blockchains may have different challenges in implementing blockchain. The key challenges are "technological immaturity," "environmental problems," and "organizational issues."
Kwok and Koh (2019)	Literature review	Tourism	–	The authors suggest that "market maturity," "political issues," "absence of regulation," and "energy consumption" are the most important challenges.
Biswas and Gupta (2019)	DEMATEL	"Banking, financial payments, railways, logistics, shipping, digital media, content distribution, software services, e-commerce, and data analytics"	India	"Scalability" and "sustainability costs" are the most important cause and effect barriers, respectively.
Yildizbasi (2021)	Pythagorean Fuzzy Analytical Hierarchy Process	Renewable Energy	Not specified	"High development costs" and "lack of acceptance by firms" are the most significant barriers to blockchain adoption.
Yadav et al. (2020)	ISM-DEMATEL-FUZZY MICMAC	Agricultural Supply Chain	India	"Lack of government regulation" and "lack of trust among agro-stakeholders" are the most important barriers to adopting blockchain.
Sahebi et al. (2020)	Fuzzy DELPHI and Best-Worst Method	Humanitarian Supply Chain	Not specified	"Regulatory uncertainty", "lack of knowledge/ employee training" and "high sustainability costs" are the most essential barriers.
Saheb and Mamaghani (2021)	Delphi using semi-structured interviews	Banking	Europe, Asia, and the Middle East	The most important barriers to blockchain adoption in the banking industry are "organizational and environmental," "lack of understanding by top managers," "compliance and regulatory requirements," and "marketing noise."
Farooque, Jain, Zhang, and Li (2020)	Fuzzy DEMATEL	Manufacturing and Retailing	China	The most vital barriers are "immaturity of technology," and "technical challenges for collecting supply chain data in real time."
Sydow et al. (2020)	In-depth interviews	Blockchain	Kenya	The main barriers are as follows: "sufficient technical capacity," "appropriate regulative interventions," and "the adoption of decentralization logics."
Zhou et al. (2020)	AHP and PESTEL	Maritime	Singapore	"Cost of implementation," "lack of experienced partners," and "lack of data privacy" are the most significant blockchain adoption barriers.
Lohmer and Lasch (2020)	In-depth interviews	Technology consulting	Germany	"Inter-organizational," "intra-organizational," "technology and external barriers" are equally important.
Kouhizadeh et al. (2021)	DEMATEL	Generic	USA	"Technological and external barriers" are the most important barriers to improving supply chain sustainability.
Dutta, Choi, Somani, and Butala (2020)	Literature review	"Shipping, manufacturing, automotive, aviation, finance, technology, energy, healthcare, agriculture and food, e-commerce, and education"	–	The study explores "organizational," "technical," and "operational" challenges. The authors suggest that "interoperability" is the main problem of blockchain implementation.
Sanka et al. (2021)	Literature review	Not specified	–	Challenges are classified into "technical," "regularity," "lack of understanding," and "resistance to change" categories. No comparison was made among them.
Sharma et al. (2021)	AHP-ISM-DEMATEL	Hospitality	India and The Netherlands	Developed and developing countries may have different challenges in adopting blockchain. While "lack of government regulation" is the most important barrier in India, "market immaturity" turned out to be significant in Netherland.
Zhao et al. (2019)	Literature review	Agri-food value chain management	–	The challenges identified in this study include "storage capacity and scalability," "privacy leakage," "high cost," "regulation problem," "throughput and latency issue", and "lack of skills." The authors also address potential means to deal with these challenges.
Hosseini Bamakan, Ghasemzadeh Moghaddam, and Dehghan Manshadi (2021)	Literature review	Pharmaceutical cold chain	–	The authors categorize the challenges of blockchain implementation in the pharmaceutical cold chain across five distinct groups: "security and privacy of data," "storage capacity," "uncertain development cost," "standardization," and "social challenges." They conclude that "interoperability" and "cooperation" are key issues.
Choi, Chung, Seyha, and Young (2020)	Technology Acceptance Modeling; Confirmatory Factor Analysis; Structural Equation Modeling	Not specified	Ireland	Based on their statistical analysis, the authors suggest that "complexity," "security and privacy concerns," and "implementation costs" have positive causal relationships with "organizations' resistance." However, "maturity," "compatibility,"

(*continued on next page*)

Table 1 (*continued*)

Paper	Method	Industry	Country	Main Findings
				and “scalability” have a negative causal relationship with “organizations’ resistance to blockchain.”
Bag, Viktorovich, Sahu, and Sahu (2021)	Fuzzy DEMATEL	Steel	Not specified	“Lack of management vision” and “cultural differences among supply chain partners” are the most influencing barriers, while “collaboration challenges” and “hesitation and workforce obsolescence” are the most influential barriers to blockchain adoption in GSCM.
Caldarelli, Zardini, and Rossignoli (2021)	Structured interviews	Textile	Italy	The barriers are classified into “technological,” “organizational,” and “environmental” barriers. The authors discuss how to handle those barriers based on expert views.
Rana et al. (2021)	ISM-MICMAC	Government	India	In an ISM model, the bottom level is comprised of challenges such as “lack of standards” and “lack of validation,” while the topmost level includes dependent challenges such as “adoption of blockchain in the public sector.”

adoption of new idea, practice, or product depends on the perception of people or organizations that see the innovation as innovative or new. According to the DOI, technology spreads among the participants of a society via the actual innovation, adopters, communication channels, time, and social system.

In addition, the adoption rate of technology is different for individuals and organizations. The adopters are categorized into five groups based on the speed of their adoption of the innovation in question: innovators (first to try the innovation), early adopters (opinion leaders), early majority (adopts innovations earlier than average individual), late majority (adopts innovation after it has been tested by the majority of the population), and laggards (conservative people who are skeptical of change). When the innovation reaches a critical mass, then it shows that innovation is self-sustaining, meaning it is spread among the majority of the social system.

The other aspect of DOI is the stages of the innovation-decision process. According to Rogers (2003), “the innovation-decision process involves five steps: (1) knowledge, (2) persuasion, (3) decision, (4) implementation, and (5) confirmation”. In this study, blockchain adoption challenges in the tourism industry are viewed through the lenses of DOI theory and linked to the stages of the innovation-decision process of DOI (Rogers, 1963). Specifically, the first stage is knowledge. Knowledge means how costumers and decision makers are aware of blockchain, what exactly it is, and how the stakeholders in the tourism industry can use it. The second stage is called persuasion, meaning tha the stakeholders in tourism industry have formed a positive or negative attitude about its adoption. This stage is followed by the decision on whether the stakeholders adopt blockchain. If blockchain is adopted, then the next stage is the implementation of blockchain in tourism industry. In the last stage (confirmation stage), individuals or organizations look for support for their decisions.

3. Methodology

A four-phase decision framework was used to examine the challenges of embracing blockchain to increase the sustainability of the tourism industry (see Fig. 1). In the first phase, a comprehensive literature review was conducted to identify the challenges to blockchain adoption. They were then finalized through an expert review. In the second phase, a rough Interpretive Structural Modeling (ISM) methodology was applied to reveal the contextual relationship among the challenges. In the third phase, a Cross-Impact Matrix Multiplication (MICMAC) analysis was utilized to categorize the challenges in terms of their driving and dependence powers. In the last phase, the challenges of blockchain adoption in tourism industry are linked to the stages of the innovation-decision process of DOI.

3.1. Background on rough sets

Traditional mathematical logic is unable to handle data that represent subjective or ambiguous human ideas, such as “strong importance” or “weak relationship”. This ambiguity is often encountered in problems with multiple criteria. The rough set theory proposed by Pawlak (1991; 1982) is an excellent mathematical tool for analyzing an ambiguous explanation of multiple objects (i.e., named actions or alternatives in decision problems) (Greco, Matarazzo, & Slowinski, 2001). Rough numbers, based on rough set theory, were first introduced by Zhai et al. (2008) to address the subjective judgments of experts or decision makers by defining boundary ranges. A rough number is usually defined to include a lower limit, an upper limit, and a rough limit derived from the original data. Hence, it can better capture experts’ true feelings and boost the objectivity of decision-making without the need for additional data (Zhu et al., 2015). Preliminary information on rough sets is displayed in Appendix 1.

3.2. Rough-ISM

There are mainly two alternative methods available for decision makers to analyze the relationship between factors. For example, Decision Making Trial and Evaluation Laboratory (DEMATEL) asks experts to assess the pairwise relationships between variables on a scale of 0–4 (0 represents “no influence,” while 4 represents “very high influence”) (Lamba and Singh, 2018). Si et al. (2018) conducted an excellent review on the research that employed the different forms of DEMATEL, such as crisp, fuzzy, and gray. DEMATEL considers that only one of the two variables affects the other and accepts the inter-variable relationship as one-way (Kumar and Dixit, 2018). Although the scale and several extensions to DEMATEL increase the rationality of the method, that one-way view of accepting inter-variable association is considered as a weakness.

ISM, developed by Warfield (1973), is another alternative technique used to describe and depict relationships between components of a complex topic or problem. The basic idea here is to divide the system into sub elements to create a multi-level structural model that reveals the experience and knowledge inherent in a complex system. In the classical ISM concept, the contextual relations between system units are considered only as binary relations: 1 indicates the presence of a relationship, while 0 indicates its absence. It disregards the strength of the contextual relationship between system units, which has an impact on the findings of expert judgment for system unit relationships. (Parameshwaran, Baskar, & Karthik, 2015). The fuzzy linguistic approach (Lee and Lin, 2011) was proposed to increase the rationality of the ISM model while evaluating the relationship between system units. It can be argued that fuzzy ISM turns out to be more advantageous than crisp

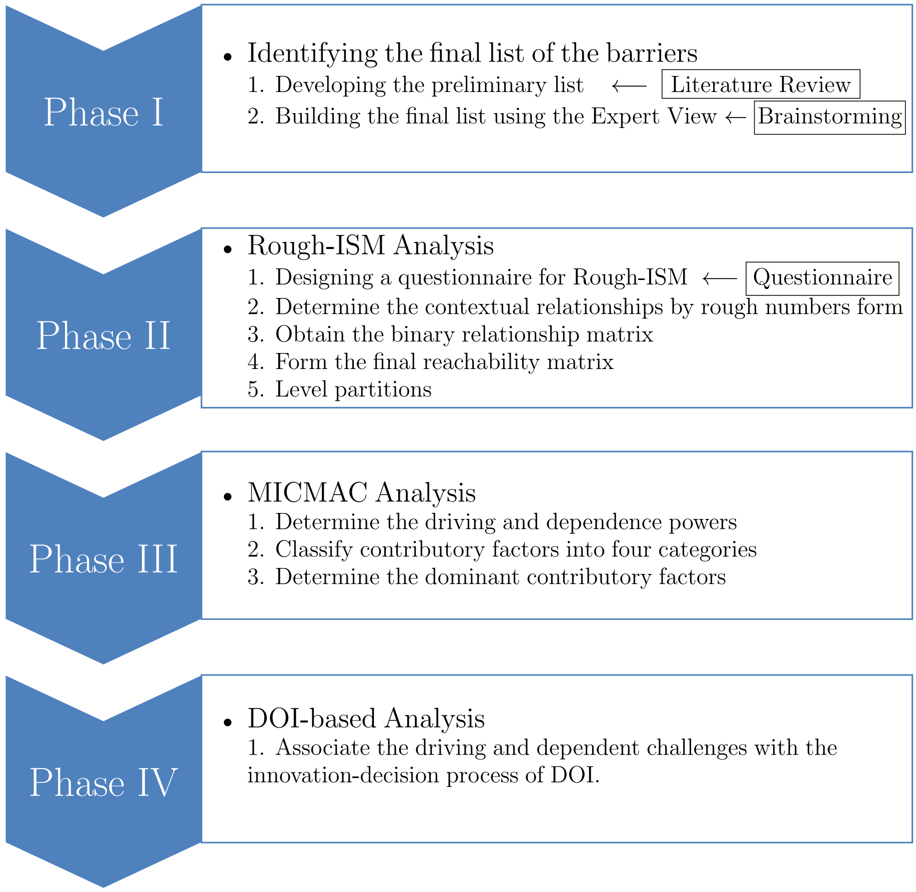

Fig. 1. The proposed framework.

DEMATEL and ISM as it provides rationality by considering the mutual relationships (Wang et al., 2018). Jayant, Azhar, and Singh (2015), Attri (2017), and Amini and Alimohammadlou (2021) provided comprehensive reviews of studies using several extensions of ISM with respect to supply chain management and other related fields.

In this study, rough-ISM was proposed to further increase the rationality in the evaluation of the relationships between system units. In the proposed rough-ISM, the associations between factors are articulated as an interval by using rough numbers. Thus, the relationship evaluation moves away from certainty in the interval form and approaches trueness. In addition, since the evaluation intervals are obtained by processing expert opinions, the reliability of the analysis increases. Thus, we suggest that more reliability, objectivity, and consistency are ensured through the proposed rough-ISM model.

A contextual link means that one variable aids the achievement of another. Therefore, the contextual relationship and corresponding direction between any two parameters *i* and *j* are defined. The following four symbols are used to represent the direction of relationship between the parameters *i* and *j* (Chander, Jain, & Shankar, 2013):

(1) “V: parameter *i* will help to achieve parameter *j*”
(2) “A: parameter *i* will be achieved by parameter *j*”
(3) “X: parameters *i* and *j* will help achieve each other”
(4) “O: parameters *i* and *j* are unrelated”

Table 2 represents the linguistic variables used in the proposed rough-ISM.

The influence of element *i* on element *j* and vice versa is exhibited in Table 3. For example, high influence on the element (*i, j*) is denoted by “*H*”, and its representative value equals 0.75. As for the element (*j, i*), the representative value is equal to 0.

Table 2
Rough linguistic scale.

“Linguistic description”	“Value”	“Notation”	“Influence scope”
“No influence”	0.00	“N″	0
“Very low influence”	0.25	“VL”	1
“Low influence”	0.50	“L″	2
“High influence”	0.75	“H″	3
“Very high influence”	1.00	“VH”	4

Table 3
Rough influence of characteristic *i* with respect to *j* and vice versa.

“Notation”	“Element (*i,j*)”	“Element (*j,i*)”	“Notation”	“Element (*i,j*)”	“Element (*j,i*)”
“V(VH)”	1.00	0.00	“X (VH, H)”	1.00	0.75
“V(H)”	0.75	0.00	“X (VH, L)”	1.00	0.50
“V(L)”	0.50	0.00	“X (VH, VL)”	1.00	0.25
“V(VL)”	0.25	0.00	“X (H, VH)”	0.75	1.00
“A (VH)”	0.00	1.00	“X (H, L)”	0.75	0.50
“A(H)”	0.00	0.75	“X (H, VL)”	0.75	0.25
“A(L)”	0.00	0.50	“X (L, VH)”	0.50	1.00
“A (VL)”	0.00	0.25	“X (L, H)”	0.50	0.75
“X (VH)”	1.00	1.00	“X (L, VL)”	0.50	0.25
“X(H)”	0.75	0.75	“X (VL, VH)”	0.25	1.00
“X(L)”	0.50	0.50	“X (VL, H)”	0.25	0.75
“X (VL)”	0.25	0.25	“X (VL, L)”	0.25	0.50
“O(N)”	0.00	0.00			

The steps of the proposed rough-ISM are displayed in Appendix 2.

3.3. MICMAC analysis

The MICMAC analysis is proposed based on the multiplication properties of matrices (Mandal and Deshmukh, 1994), which categorizes the essential factors in terms of their driving and dependence powers. (Agrawal, 2019). In this approach, the driving force and dependency power of each factor is calculated. Thus, all factors are classified into the four specified clusters: "autonomous factors," "dependent factors," "linkage factors," and "independent factors" (Ali, Rasoolimanesh, & Cobanoglu, 2020). The MICMAC analysis is frequently used to facilitate multidimensional interpretations. The method has been used in many research areas, including tourism (Lin and Yeh, 2013; Sarmah and Rahman, 2018), marketing (Sharma and Bumb, 2021), quality management (Agrawal, 2019), waste management (Sharma et al., 2020), education (Kinker, Swarnakar, Singh, & Jain, 2021; Suresh & Kesav Balajee, 2021), and manufacturing (Dubey & Ali, 2014). The steps of the MICMAC approach are summarized in Appendix 3.

3.4. DOI-based analysis

In this phase, the adoption of blockchain in the tourism industry is investigated using the diffusion of innovation (DOI) theory (Rogers, 1963). The detailed information on the theory of DOI is provided in Section 2.4.

4. Application and the results

In this section, the four-phase methodology (see Fig. 1) was applied to examine the challenges to blockchain adoption in enhancing the sustainability of tourism industry. The details of the application are provided in the following subsections.

4.1. Identifying the final list of blockchain challenges

To this end, first, a comprehensive literature review on the challenges of blockchain adoption was performed as introduced in Section 2.3. Based on the literature review in Table 1, we specified 15 blockchain adoption challenges. The title of the challenges, their descriptions, and the related references are presented in Table 4.

Once the challenges displayed in Table 4 were identified, they were presented to the Expert Group. Note that in a MCDM research, there is no hard and fast rule regarding the number of experts (Bulut & Duru, 2018). Because blockchain is such a novel technology, it is critical to choose survey respondents who have an adequate understanding and expertise with it to complete the survey. Respondents should also be familiar with sustainability in the tourism industry both theoretically and practically. Taking these two factors into account, researchers, decision makers, and practitioners who have significant knowledge of, research on, and hands-on experience in blockchain and sustainable tourism are referred to as experts in this study. We utilized a purposive sampling method enhanced by snowball recruitment to discover experts who satisfied the criteria we provided above. We began by conducting an Internet search for experts with knowledge of and experience in both blockchain and sustainable tourism.

After a two-month search on the Internet, phone calls, and virtual meetings with possible respondents, we designated twenty-five experts who fit our criteria. While thirteen of them are scholars with the average age of 35, the rest are the senior managers employed in the information system departments of major travel agencies, and hotels located in all over Europe, US, and Canada. The scholars, working for the universities located in Turkey, USA, Canada, Denmark, and Germany, have had research experiences and published various papers in the context of sustainable tourism focused on using disruptive technologies, such as big data, artificial intelligence, and blockchain technology. The scholars

Table 4
Literature on the challenges of blockchain adoption.

Challenges	Description	Reference
"Lack of technological maturity (Ch_1)"	Blockchain is considered an emerging technology. Adopters are concerned about the technology's immaturity, legislative issues, and a lack of precise and explicit business models, all of which are preventing widespread recognition. Undeveloped technology may lack the necessary level of robustness in terms of data throughput, scalability, and latency, posing a serious problem in an inter-connected ecosystem like the tourism industry. Such a deficiency will have a negative impact on the potential of blockchain toward the sustainability of the tourism industry.	Lee and Lee (2015), Biswas and Gupta (2019), Ranta et al. (2021), Toufaily et al. (2021)
"Lack of interoperability (Ch_2)"	The capacity of different apps and programs to communicate and use information is referred to as interoperability. Interoperability addresses connecting various ledgers and promoting cross-chain communication, engagement, and value transfer. In order to improve the sustainability of supply chain performance, various blockchain platforms in the tourism industry should be interoperable. However, a lack of interoperability is still a concern that hinders the effective implementation of blockchain.	Perrons and Cosby (2020), Sahebi et al. (2020), Toufaily et al. (2021), Sanka et al. (2021)
"Lack of expertise and human capital (Ch_3)"	The lack of blockchain talent remains an industry concern regarding the sustainability of the tourism industry. The recent advancement and increasing sophistication of technology have amplified the gap between the demand for competent human resources and expertise and the supply of such personnel.	Helliar, Crawford, Rocca, Teodori, and Veneziani (2020), Kamble, Gunasekaran, and Arha (2019), Choi et al. (2020)
"High cost of blockchain investment (Ch_4)"	Since blockchain is a feature-dependent technology, the final cost will vary depending on the project requirements. However, in general, a substantial capital expenditure may be required to initially implement the necessary blockchain infrastructure, which may ultimately affect the financial sustainability.	Thakur et al. (2019), Lohmer and Lasch (2020), Lin and Liao (2017), Azati Team (2021)
"Little concrete evidence of financial, social, and	Concrete benefits of blockchain in terms of	

(continued on next page)

Table 4 (*continued*)

Challenges	Description	Reference
environmental benefits (Ch_5)"	financial, environmental, and societal sustainability have yet to be sufficiently demonstrated in the tourism industry. There is little scientific and practical evidence of blockchain's impact on the sustainability of the tourism industry. The majority of studies use cases addressed focused on the pilot and planning stages.	Hackius and Petersen (2017), Kouhizadeh et al. (2021)
"Lack of accessing to blockchain technology (Ch_6)"	Some companies in the Turkish tourism industry may face difficulties accessing the proper blockchain technology due to its cost and/or low level of penetration in the industry.	Farooque et al. (2020)
"Lack of customers' awareness (Ch_7)"	Customers are not aware of blockchain and do not have sufficient information about its usage in other industries. Therefore, they should be educated regarding "the features of this technology and the implications of its use for data ownership, access, and privacy" so that the blockchain adoption rate of the companies increases to improve the social sustainability of the industry toward customers.	OECD (2020), Rugeviciute and Mehrpouya (2019)
"Lack of collaboration and coordination in the supply chain (Ch_8)"	Since blockchain projects should contain "government, developers, financial actors, start-ups, regulators, accountants, audit companies, and consultants," collaboration and coordination in the tourism industry are considered to be the main ingredients of effective blockchain implementation. In a similar vein, enhanced collaboration and coordination may improve three aspects of sustainability in the industry.	Toufaily et al. (2021)
"Conflicts with the existing business culture (Ch_9)"	Current business practices in the tourism industry may hinder successful blockchain applications. In other words, current bureaucratic processes and mindsets may be considered as major hurdles in achieving effective blockchain projects toward sustainability.	Li et al. (2019), Toufaily et al. (2021)
"Lack of top management commitment (Ch_{10})"	Support from top management is critical to successfully implementing any endeavor toward sustainability. Technology adoption requires organizational leadership, particularly in terms of championing innovation. However, some managers may fail to exhibit essential support to embracing blockchain and sustainability. Therefore, a lack of top management support may prevent successful blockchain applications in the sustainability of the tourism industry.	Kouhizadeh et al. (2021), Toufaily et al. (2021)
"Lack of legislation and standardization (Ch_{11})"	Each blockchain initiative must take consumer and data protection laws into account. If blockchain is used to construct a decentralized and distributed supply chain model, established market responsibilities and accountabilities may be altered. As a result, a new regulatory system should reflect all of these developments, which ultimately affect the three pillars of sustainable tourism.	Bilal, Khan, Thaheem, and Nasir (2020), Wang et al. (2021), Sharma et al. (2021)
"Lack of governmental support and effective incentive programs (Ch_{12})"	Governments aren't proactive in supporting blockchain education and training. Furthermore, they are sometimes hesitant to invest in new startup companies that are developing unique solutions to enable new business models through either directly providing cash or the use of tax-related incentives.	Wang et al. (2021), Sharma et al. (2021)
"Lack of security and privacy (Ch_{13})"	Security is one of the most important problems that practitioners are discussing with public blockchains. Even if private blockchains are considered to be more secure, there are still concerns with respect to data security in blockchain applications. When compared to typical centralized databases, blockchain is used to reveal more information to other parties given the necessity to distribute data across numerous peers.	Nakamoto (2008), Makhdoom et al. (2019), Spathoulas et al. (2021), Sanka et al. (2021)
"Lack of CSFs (Ch_{14})"	CSFs are defined as a set of factors that, if effectively implemented, will ensure that the organization's or project's goals and mission are met. To put it another way, the organization's performance will be inadequate if the outputs of these factors are not satisfactory. A lack of CSFs for the sustainability of the tourism industry may render potential blockchain projects ineffective.	Thierauf (1982), Gates (2010)

(*continued on next page*)

Table 4 (*continued*)

Challenges	Description	Reference
"Lack of organizational policies and strategies (Ch_{15})"	Policies and strategies articulate the governance culture. They address more than how to satisfy legislative requirements. They are also needed to enable the performance objectives of the organization. Therefore, not having clear and well-defined organizational policies and strategies with respect to the sustainability of the tourism industry about an innovative technology implementation initiative is a recipe for a failure.	Lohmer and Lasch (2020), Wang et al. (2019)

are all male. The senior executives, five of whom are women, have over ten years of management experience in R&D efforts on sustainability, machine learning, artificial intelligence, and blockchain technology. Their average age is 38. To ensure the reliability of the expert assessments, several online presentations were performed to clarify the goal of the study. In addition, a guideline explaining each challenge was provided to the experts.

Two virtual meetings, each lasting about 30 min, were held in January 2022 after the complete list shown in Table 4 was presented to the expert group. In these sessions, the expert group examined the list of challenges exhibited in Table 4. The expert group concluded that no change was required on the list. Hence, RQ_1 has been addressed.

4.2. Rough-ISM

In the second phase, rough-ISM methodology proposed in this study was used to determine the contextual relationship among the challenges. First, a panel of 25 experts evaluated the relationships between the challenges using the scales in Tables 2 and 3 This evaluation process was conducted in March 2022. Then, the expert opinions were converted into rough numbers by using the properties of the rough sets in Eqs. (1)–(11). The rough direct relationship matrix was created by plugging the rough number forms of the expert opinions into Eqs. (17) and (18) while the rough direct relation matrix was converted into the direct relation matrix by Eq. (20). Calculations were made with software[1] coded in Visual Basic Application (VBA) language. The software can be used for academic purposes by referencing this article.

By averaging the elements of the direct relationship matrix, the threshold value was calculated as $d' = 0.2347$. With the rule of Eq. (23), the initial reachability matrix was obtained. Then, The final reachability matrix was calculated by applying the transitivity rule. The transitivity rule can be summarized as follows: If a variable L is associated with variable M and a variable M is associated with variable N, then L is naturally associated with M. The final reachability matrix is given in Table 5, where transitivity is emphasized as 1*. The driving power and dependence power for each challenge are also exhibited in Table 5.

The final reachability matrix provides the reachability and antecedent sets for each challenge. While the reachability set includes the challenge itself and the challenges it can affect, the antecedent set includes the challenge itself and the challenges that affect it. In addition, by intersecting these sets for all the challenges, intersection sets were obtained. Challenges with the same reachability and intersection sets are at the top of the ISM hierarchy. The top-level challenge (s) in the hierarchy would not lead any other challenge (s) above its level. The top-level challenge is segregated from the other challenges once it has been determined. The same procedure was used to discover the next level's top-level challenge (s). This process was repeated until the level of each factor was determined (Table 6). The hierarchy and the final model were built with the help of these levels.

As evident from Table 6, challenges 7, 9, and 14 did not lead to any other challenge. Therefore, they were assigned to level 1 and then removed in the following iteration. Similarly, the challenges 3, 5, and 8 were at level 2, while challenges 4, 6, 10, 11, 12, 13, and 15 were at level 3. In addition, challenge 2 was located at level 4, while challenge 1 was at level 5. The rough ISM-based model built after removing the transitivities is shown in Fig. 2. In this model, an arrow pointing from i to j indicates a relationship between challenges i and j.

The findings of the proposed rough-ISM model used in this study indicated that "*lack of technical maturity (Ch_1)*" and "*lack of interoperability (Ch_2)*" lie at the bottom. Next, they indicated that "*lack of customers' awareness (Ch_7)*", "*conflicts with existing business culture (Ch_9)*", "*lack of CSFs (Ch_{14})*", "*lack of expertise and human capital* (Ch_3)", "*little concrete evidence of financial, social, and environmental benefits (Ch_5)*", and "*lack of collaboration and coordination (Ch_8)*" are located at the top. Lastly, the proposed rough-ISM concluded that "*high cost of blockchain investment (Ch_4)*", "*lack of accessing blockchain technology (Ch_6)*", "*lack of top management commitment (Ch_{10})*", "*lack of legislation and standardization (Ch_{11})*", "*lack of governmental* support *and effective incentive programs (Ch_{12})*", "*lack of security and privacy (Ch_{13})*", and "*lack of organizational policies (Ch_{15})*" lie between the top and bottom levels.

4.3. MICMAC analysis

The result of the MICMAC analysis indicates the driving power and dependence power of the challenges. These computations were achieved by using Eqs. (26)–(28). The MICMAC diagram with the challenges classified in four clusters is given in Fig. 3. No challenge is included in the first cluster (weak driving power and weak dependency). In other words, there is no autonomous challenge. This means that all the challenges included in the model are interrelated. The second region, the dependent region, includes challenges with high dependence on other challenges but low driving power. Note that these challenges are at high levels in the ISM-based model. The third cluster includes the linkage challenges that have a strong driving force and strong interdependence at the same time. Since these challenges depend on other challenges and direct higher-level factors, they act as mediators between the two clusters. The driving challenges that have strong driving power but weak dependencies are in the fourth cluster and located at the bottom of the ISM model.

In this study, a validation through a virtual meeting was conducted to validate the results obtained in the proposed Rough ISM-MICMAC. In order to accomplish that, the expert panel was first given the findings shown in Fig. 3. After that, the expert group participated in a virtual meeting for around 40 min. This online meeting was conducted in March 2022. During the meeting, the driving, linkage, and dependent challenges were explained to the expert group. Then, they examined and discussed their reasonableness. Finally, a consensus was achieved on the validation of the results, and they concluded that no change is necessary. Thus, RQ_2 has been answered.

5. Discussion and implications

In this study, note that reference to the previous studies should be done with caution since they were conducted in different industries that exemplified dissimilar settings. Our findings indicated that none of the challenges lie in the autonomous cluster that displays weak driving and dependence power. In other words, we suggest that all of the challenges play a significant role in blockchain adoption. In additions, dependent challenges illustrate weak driving and strong dependence power. Put

[1] https://github.com/ahmetoztel/Rough-ISM.

Table 5
The final reachability matrix of the challenges.

Ch	Ch_1	Ch_2	Ch_3	Ch_4	Ch_5	Ch_6	Ch_7	Ch_8	Ch_9	Ch_{10}	Ch_{11}	Ch_{12}	Ch_{13}	Ch_{14}	Ch_{15}	Driving Power
Ch_1	1	1	1*	1	1	1	1	1	1	1	1	1	1	1*	1	15
Ch_2	0	1	1*	1	1	1	1	1	1	1	1*	1	1	1*	1	14
Ch_3	0	0	1	0	1*	0	1*	1	1	0	0	0	0	1*	0	6
Ch_4	0	0	1*	1	1	1	1	1	1	1	1*	1*	1*	1*	1*	13
Ch_5	0	0	1	1*	1	1*	1	1	1	1	1	1	1*	1	1	13
Ch_6	0	0	1*	1*	1	1	1	1	1	1*	1*	1*	1*	1*	1*	13
Ch_7	0	0	1*	0	0	0	1	1*	1	1	0	0	0	1*	1*	7
Ch_8	0	0	1*	1*	1	1*	1	1	1	1*	1*	1*	1*	1	1*	13
Ch_9	0	0	0	0	0	0	1*	0	1	0	0	0	0	1	0	3
Ch_{10}	0	0	1	1*	1*	1*	1	1	1	1	1*	1*	1*	1	1	13
Ch_{11}	0	0	1	1*	1*	1	1	1	1	1	1	1	1	1	1	13
Ch_{12}	0	0	1	1	1*	1	1	1	1	1	1*	1	1*	1	1	13
Ch_{13}	0	0	1*	1*	1	1*	1	1	1	1	1*	1*	1	1	1*	13
Ch_{14}	0	0	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1	1*	13
Ch_{15}	0	0	1	1*	1*	1*	1	1	1	1*	1*	1*	1*	1	1	13
Dependence Power	1	2	14	12	13	12	15	14	15	13	12	12	12	15	13	175/175

Table 6
Levels of the key challenges.

Ch (Ch_i)	"Reachability set"	"Antecedent set"	"Intersection"	"Level"
Ch_1	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	1	1	V
Ch_2	2,3,4,5,6,7,8,9,10,11,12,13,14,15	1,2	2	IV
Ch_3	3,5,7,8,9,14	1,2,3,4,5,6,7,8,10,11,12,13,14,15	3,5,7,8,14	II
Ch_4	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,4,5,6,8,10,11,12,13,14,15	4,5,6,8,10,11,12,13,14,15	III
Ch_5	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,3,4,5,6,8,10,11,12,13,14,15	3,4,5,6,8,10,11,12,13,14,15	II
Ch_6	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,4,5,6,8,10,11,12,13,14,15	4,5,6,8,10,11,12,13,14,15	III
Ch_7	3,7,8,9,10,14,15	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	3,7,8,9,10,14,15	I
Ch_8	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,3,4,5,6,7,8,10,11,12,13,14,15	3,4,5,6,7,8,10,11,12,13,14,15	II
Ch_9	7,9,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	7,9,14	I
Ch_{10}	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,4,5,6,7,8,10,11,12,13,14,15	4,5,6,7,8,10,11,12,13,14,15	III
Ch_{11}	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,4,5,6,8,10,11,12,13,14,15	4,5,6,8,10,11,12,13,14,15	III
Ch_{12}	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,4,5,6,8,10,11,12,13,14,15	4,5,6,8,10,11,12,13,14,15	III
Ch_{13}	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,4,5,6,8,10,11,12,13,14,15	4,5,6,8,10,11,12,13,14,15	III
Ch_{14}	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15	3,4,5,6,7,8,9,10,11,12,13,14,15	I
Ch_{15}	3,4,5,6,7,8,9,10,11,12,13,14,15	1,2,4,5,6,7,8,10,11,12,13,14,15	4,5,6,7,8,10,11,12,13,14,15	III

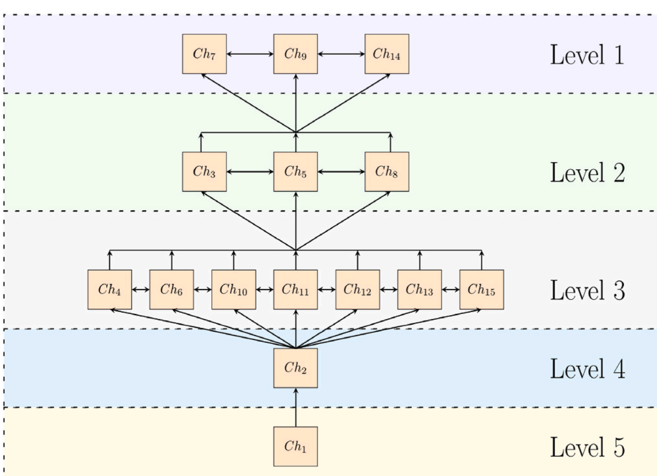

Fig. 2. Ism model.

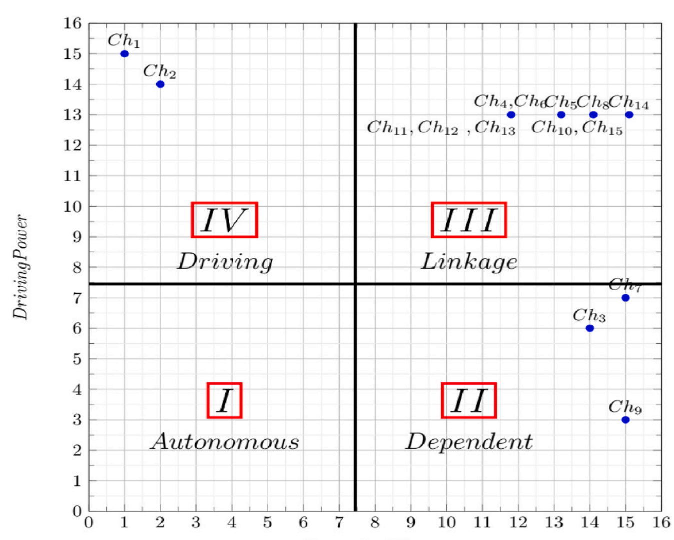

Fig. 3. Driving vs. dependence power using MICMAC analysis.

another way, these challenges show the features of output factors in a system. Our findings reveal "*lack of expertise and human capital* (Ch_3)", "*lack of customers' awareness* (Ch_7)", and "*conflicts with existing business culture* (Ch_9)" are highly driven and dependent on the other input challenges in the sustainability of the tourism industry. Note that studies on the challenges/barriers to blockchain adoption in industries suggested various effects or dependent variables. For example, Yadav et al. (2020) maintained that lack of scalability and lack of interoperability are the main dependent challenges—a finding that contradicts our results. However, Yadav et al. (2020) also maintained that resistance to change is another important dependent challenge, which is consistent with our findings. In another example, Sharma et al. (2021) argued that resistance to change, lack of top management commitment, and lack of knowledge and expertise turned out to be significant dependent challenges, which somewhat corroborates our findings.

Linkage challenges are both highly influential and highly dependent. They demonstrate the features of both strong driving and dependence power with respect to blockchain adoption for the sustainability of the tourism industry. These are generally mid-level challenges, and "*high cost of blockchain investment (Ch_4)*", "*little concrete evidence of financial, social, and environmental benefits (Ch_5)*", "*lack of accessing blockchain technology (Ch_6)*", "*lack of collaboration and coordination (Ch_8)*", "*lack of top management commitment (Ch_{10})*", "*lack of legislation and standardization (Ch_{11})*", "*lack of governmental* support *and effective incentive programs (Ch_{12})*", "*lack of security and privacy (Ch_{13})*", "*lack of CSFs (Ch_{14})*", and "*lack of organizational policies (Ch_{15})*" came under this cluster.

Driving challenges, on the other hand, exhibit strong driving and weak dependent power. That is, the challenges in this domain have strong impact on all of the other challenges in the sustainability of the tourism industry. This study found that "*lack of technical maturity (Ch_1)*" and "*lack of interoperability (Ch_2)*" are the driving blockchain adoption challenges in Turkish tourism for building more sustainability. We argue that the findings on driving challenges in this study corroborate the ideas of Farooque et al. (2020), Kouhizadeh et al. (2021), Dutta et al. (2020), and Hosseini Bamakan et al. (2021), who suggested that immaturity of technology and lack of interoperability are the main causes or drivers of blockchain adoption. However, Yadav et al. (2020), Sahebi et al. (2020), and Sharma et al. (2021) concluded that lack of government regulations are the main cause barriers to blockchain adoption, while our findings suggest that "*lack of legislation and standardization (Ch_{11})*" and "*lack of governmental* support *and effective incentive programs (Ch_{12})*" are linkage challenges, implying that they demonstrate both the features of strong driving and dependence power.

5.1. Linking the challenges to the theory of DOI

The results of the study were also evaluated through the innovation-decision process of DOI theory. This process has five stages, and our results can be categorized accordingly, as shown in Table 7. The decision, implementation, and confirmation stages do not exist in our results since the extant literature and the postulations of the theory of DOI suggest that blockchain technology is still nascent in the tourism industry globally (Flecha-Barrio, Palomo, Figueroa-Domecq, & Segovia-Perez, 2020).

Table 7 shows that knowledge stage is associated with the dependent challenges, such as "*lack of expertise and human capital (Ch_3)*" and "*lack of customers' awareness (Ch_7)*", indicating that there is still not enough knowledge about blockchain as a technology, which justifies its non-existence in the tourism industry. The persuasion stage has a mix of dependent, driving, and linkage challenges, which implies that the high cost of blockchain investment, the unknown results of blockchain adoption for the organization, lack of technological maturity and interoperability, as well as organizational issues such as lack of management commitment and lack of organizational policies are the main reasons for the tourism industry's unwillingness to adopt blockchain. These results are also in line with those of previous research regarding blockchain adoption in tourism, suggesting the difficulty of finding practical business models, uncertainty regarding economic returns on investment, lack of infrastructure, lack of regulations concerning blockchain, and concerns about safety of transactions (Pai et al., 2018). Thus, RQ_3 has been addressed.

Table 7
Blockchain adoption stages and driving forces.

Innovation-decision process stage	Challenges	Blockchain adoption challenges
Knowledge	dependent	"Lack of expertise and human capital" (Ch_3)
Knowledge	dependent	"Lack of customers' awareness" (Ch_7)
Persuasion	linkage	"High cost of blockchain investment" (Ch_4)
Persuasion	linkage	"Little concrete evidence of financial, social, and environmental benefits" (Ch_5)
Persuasion	linkage	"Lack of collaboration and coordination in the supply chain" (Ch_8)
Persuasion	dependent	"Conflicts with the existing business culture" (Ch_9)
Persuasion	linkage	"Lack of top management commitment" (Ch_{10})
Persuasion	linkage	"Lack of organizational policies" (Ch_{15})
Persuasion	driving	"Lack of technological maturity" (Ch_1)
Persuasion	driving	"Lack of interoperability" (Ch_2)
Persuasion	linkage	"Lack of access to blockchain technology" (Ch_6)
Persuasion	linkage	"Lack of legislation and standardization" (Ch_{11})
Persuasion	linkage	"Lack of governmental support and effective incentive programs" (Ch_{12})
Persuasion	linkage	"Lack of security and privacy" (Ch_{13})
Persuasion	linkage	"Lack of CSFs" (Ch_{14})

On the other hand, although the blockchain implementations in the tourism industry is still at the knowledge and persuasion stages in general, it is noteworthy to discuss some of the early endeavors to its adoption in various countries. For example, decentralized applications (dApps) enable people to connect with blockchain technology on a much more frequent and comfortable manner, including via their smartphones or web browsers (Nam et al., 2021). Ozdemir et al. (2020) compared various early applications of dApps through a list of blockchain criteria. In their analysis, the authors considered Nocturus, Smart Trip, Further, and GOeureka as some of the initial applications of blockchain in tourism industry. They concluded that these dApps are different in terms of blockchain governance model, blockchain platforms, types of consensus, and use of cryptocurrency, smart contracts and tokens. They also concluded that blockchain is still a promising technology, with new standards and variants being developed all the time. As a result, it may be claimed that, at least until further innovations, the recent blockchain technology is only suitable for particular applications. Joo, Park, and Han (2021) investigated how blockchain and smart contracts may be used in the tourism industry and how they can be used to improve existing tourism ecosystems. To this end, they examined several early blockchain applications including tripEcoSys, Travel Chain, DeskBell Chain, Winding Tree, and TravelFlex.

According to Spencer, Buhalis, and Moital (2012), leadership is the most crucial factor for small tourism business in terms of technology adoption. Their study indicates the level of technology adoption in these firms and the type of leader who is responsible for technology adoption. The leaders in these firms are categorized based on their technological acceptance such as resistors, enforcers, stabilizers, reactors, and converters. The highest adoption rate occurs when the leader is a converter defined as risk taker, highly educated, and technologically experienced. They conclude that technology adoption decisions need to be supported by market research and not just the subjective intuition of firm leaders shaped by personal experiences. The converters are similar to early adopters in DOI, who are more educated, have a higher status in society, are better accepted in their community, and have larger and more specialized operations (Rogers, 2003).

Some of the challenges to blockchain adoption in the tourism industry such as lack of technological maturity, lack of interoperability, and high cost of investment are associated with the limitations of technological infrastructure. Thus, businesses with access to technology can accomplish technological implementations that are constrained by infrastructure. (Inwood, Sharp, Moore, & Stinner, 2009).

5.2. Managerial and policy implications

This study has a number of policy implications. First, the findings provide innovative direction for key stakeholders in the tourism industry as they move toward greater sustainability. Our findings suggested that, although blockchain can aid in enhancing the sustainability of tourism industry, a lack of technical maturity and lack of interoperability have the highest driving powers and that these barriers must be addressed by decision makers if blockchain is to be successfully and widely adopted to improve the sustainability of the tourism industry. These are not unknown problems in the information technology literature. For example, Lee and Lee (2015) explored the issues with technologies that haven't been thoroughly evaluated. Such technologies may lack the necessary level of robustness in terms of data throughput, latency, and privacy, posing a serious predicament for a complicated ecosystem like tourism industry. To enhance the level of blockchain adoption in the tourism industry, more study is needed to analyze and improve the technological maturity and interoperability of blockchain. Yadav et al. (2021) suggested that the issues of trust, transaction cost, data management, and data security that are associated with technical maturity of blockchain should be addressed.

Furthermore, our findings suggest that improvement in linkage challenges, including "high cost of blockchain investment (Ch_4)", "little concrete evidence of financial, social, and environmental benefits (Ch_5)", "lack of accessing blockchain technology (Ch_6)", "lack of collaboration and coordination (Ch_8)", "lack of top management commitment (Ch_{10})", "lack of legislation and standardization (Ch_{11})", "lack of governmental support and effective incentive programs (Ch_{12})", "lack of security and privacy (Ch_{13})", "lack of CSFs (Ch_{14})", and "lack of organizational policies (Ch_{15})", also depend on the technical maturity and interoperability of blockchain. For example, the existence of governmental support and effective incentive programs is mostly contingent on the technical maturity and interoperability of blockchain. More specifically, unless governments are convinced that blockchain is technologically mature and interoperable, support and incentives for its implementation may be deemed insufficient by the tourism industry. In a similar vein, our findings suggest that a sufficient level of top management commitment and the existence of effective organizational policies and CSFs for the sustainability of the tourism industry are dependent on improvements in blockchain technology and its interoperability.

In addition, integrating tourism operations with blockchain may provide its own set of challenges with administration, privacy, and security. Put differently, the main concern is whether the additional layer of advanced technology adds to the practical application's complexity. The more pressing concern is whether this integration will result in a win-win situation for all parties involved (Yadav et al., 2021) To gain further blockchain buy-ins from tourism industry stakeholders, along with the development efforts of blockchain worldwide, governments should also support activities toward enhancing blockchain's technical maturity. Fragnière et al. (2022) argued that governments must take this issue into consideration and adopt measures to support the growth of blockchain in tourism industry. More specifically, governments could achieve this with the support of its national research institutes and the ministries of tourism through funding projects that focus on improving the effectiveness of blockchain in terms of indicators such as throughput, scalability, trust, privacy, and interoperability. Beyond technical maturity, blockchain's feasibility for sustainability in the tourism industry will be enhanced by other types of governmental support. Identified as linkage challenges in our study, the second most successful strategy to boost investor confidence is to create incentive programs and pass new regulations. While companies may be willing to test innovative technologies, commercialization may be impossible without effective laws and incentive programs originating from governments.

Lastly, our findings reveal that "*lack of expertise and human capital* (Ch_3)", "*lack of customers' awareness* (Ch_7)", and "*conflicts with existing business culture* (Ch_9)" are highly driven and dependent on the other input challenges in the tourism industry. This finding is consistent with Yadav et al. (2020) and Sharma et al. (2021), implying the Expert Group concluded that the challenges of insufficient human capital, customers' awareness, and negative business culture are mostly contingent on improvements in the driving challenges (e.g., the technological maturity and interoperability of blockchain). The results of the proposed framework demonstrate both the associations among the blockchain adoption challenges and the linkages of those challenges to DOI. We argue that blockchain adoption in the tourism industry is still in its early stages, which is consistent with the argument of Valeri and Baggio (2021), indicating that there are still too few actual implementations to analyze and evaluate. The tourism industry is lacking knowledge regarding blockchain, and it is not convinced that blockchain will be beneficial to the industry. In addition, the tourism industry should focus on tokens and non-fungible tokens, which is highly important for understanding the perspectives of travelers. As Treiblmaier (2021) indicated, tokens signify value and are likely to build the token economy in near future.

In summary, given the driving and dependent challenges of blockchain adoption in the sustainability of tourism industry, we suggest that unless the technical maturity and interoperability of blockchain are at least partly achieved, stakeholders in the tourism industry may not be eager to heavily invest in blockchain applications to enhance the industry sustainability. The guidelines for the stakeholders are displayed in Table 8.

5.3. Theoretical implications

In this study, the driving and dependence powers of blockchain adoption challenges in the tourism industry were identified using an integrated decision framework comprising rough ISM-MICMAC. Formal decision frameworks provide a decision-making structure, which can lead to a process yielding well-grounded decisions. Hence, we claim that the formalized decision framework in this study aims to improve decision makers' understanding of the problem by aiding them in identifying the best course of action by taking into account their own goals, values, and objectives, as well as those of other stakeholders. To put another way, instead of striving to replace intuition or experience, the proposed decision framework serves to complement and challenge it. It aims to make subjective judgments explicit, as well as the method through which they are considered.

Moreover, the objective of this study is not to reach a final best answer to the challenges of adopting blockchain in the tourism industry but to construct something suitable to assist a decision maker in making decisions that are consistent with his or her objectives. In conclusion, procedure is extremely important in each phase of the suggested decision framework, and each step should be accomplished carefully and attentively.

6. Conclusions

Tourism has numerous benefits for both visitors and residents of host communities. Yet, these positive outcomes are often accompanied by

Table 8
Recommendations for the stakeholders.

Stakeholders	Responsibilities
Governments	• Constructing a regulatory structure for blockchain • Creating a powerful incentive system • Allocate more research funds to national research institutes for blockchain projects on improving tourism sustainability • Establishing macro policies towards blockchain
Non Governmental Organizations	• Evaluating the financial gains from using blockchain in the short- and long-term • Increasing customer awareness towards blockchain
Organizations	• Guaranteeing the support of the top management • Achieving adequate training for blockchain • Assessing the feasibility of blockchain adoption • Adopting effective blockchain strategies.
Supply Chains	• Forming the right supply chain tactics towards effective blockchain implementations. • Developing technically effective blockchain systems.

adverse social and environmental impacts. Sustainable tourism enables more ecologic viability, economic feasibility, and societal desirability and helps maximize the potential benefits of tourism, while reducing or eliminating the drawbacks. Existing research suggests that blockchain, as s disruptive technology, may have a positive impact on sustainability of various industries. However, they also suggest that despite its advantages, blockchain has certain shortcomings and challenges with respect to scalability, data security, speed, regulations, interoperability, technological immaturity and so on. To date, several studies have been conducted on the challenges of adopting blockchain in various industries. Nonetheless, no prior analysis has been performed on the challenges to blockchain adoption in order to help improve sustainable tourism performance. Consequently, in this study, the first step was to identify the challenges to blockchain adoption using both a thorough literature review and consultation with an expert group. Then, a rough ISM and MICMAC based decision framework was proposed to discover the driving and dependence powers of the challenges based on the expert data. Finally, our findings indicated that *lack of technical maturity* and *lack of interoperability* are highly significant for the success of blockchain implementation in the industry. They also indicated that blockchain implementations in the tourism industry is still at the knowledge and persuasion stages through the theory of DOI. The results will contribute to better macro- and micro-level policymaking in the tourism industry. Our findings can also be used as a benchmark - as long as country-specific peculiarities are considered.

The contributions of this study are as follows: (1) To date, there have been several industries and (or) country specific studies regarding the challenges to blockchain implementation. However, no prior research has scrutinized the challenges to blockchain adoption in order to improve the sustainability performance of the tourism industry. In this study, the list of challenges to blockchain adoption was determined via both a literature analysis and expert viewpoints. (2) To date, some research has been performed to reveal associations between the challenges to blockchain adoption. However, no study has analyzed the driving and dependency powers of the challenges towards the sustainability of the tourism industry based on expert data. In this study, rough ISM-MICMAC was proposed to demonstrate the associations among blockchain adoption challenges in order to improve the sustainability of the tourism industry. (3) Blockchain adoption challenges are linked to the innovation-decision process of DOI to identify the relevant stages of blockchain adoption. (4) Managerial and policy implications of our findings were also discussed.

There are certain limitations of this study, which opens up a number of research opportunities. First, this study is based on data gathered from a small number of experts. Though the number of experts included in this study is adequate to support the study's primary conclusions, we believe that expanding the number of experts would be advantageous. Thus, further research might be undertaken with a larger expert group, as well as experts from other countries. In other words, country-specific studies should be conducted through considering several peculiarities for those countries. Moreover, a similar study in a different sector that has already adopted blockchain such as finance could be conducted to see the adoption stages of blockchain according to the theory of DOI and combine it with recommendations of how the industry has overcome the challenges of blockchain adoption. This practice may provide substantial benefits of facilitating the adoption of blockchain technology in the tourism industry. In a similar vein, future research can be conducted to evaluate blockchain diffusion using methods including Technology Acceptance Model and Unified Theory of Acceptance and Use of Technology. Finally, to better manage the subjectivity of expert opinions, more robust methods based on new fuzzy and rough set extensions could be applied.

Author contributions

Ismail Erol: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Validation, Supervision, Formal analysis. **Irem Onder Neuhofer**: Methodology, Writing – review & editing, Investigation, Validation, **Tarik Dogru (Dr. True)**: Methodology, Writing – review & editing, Investigation, Validation, **Ahmet Oztel**: Methodology, Validation, Writing – original draft. **Ali C. Yorulmaz**: Formal analysis, Validation, Data curation, Cory Searcy: Writing – review & editing, Investigation.

Impact statement

The contribution of this research is two-fold: first, it investigates the challenges to blockchain adoption to help improve sustainability in the tourism industry. Second, it associates the key challenges to the innovation-decision process of DOI theory. To this end, the challenges to blockchain adoption were identified through a comprehensive literature review. Then, a novel rough ISM-MICMAC-based decision framework was proposed to discover the driving and dependence powers of the challenges based on the expert data. The results suggest that lack of technical maturity and lack of interoperability are the most important challenges of blockchains in the tourism industry. The method formation, findings, discussion, and implications of this study could be informative for practitioners, allowing them to better grasp the driving, independent, and linkage factors for blockchain adoption in tourism industry to achieve more sustainability. This research is also attractive to researchers due to the framework incorporating qualitative into quantitative methods.

Declaration of competing interest

None.

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None.

Appendix 1

"Let U be a universe comprising all objects and X be a random object from U. Then, it is assumed that there exists set build with k classes denoting DMs preferences, $R = (J_1, J_2, \ldots, J_k)$ with condition $J_1 < J_2 <, \ldots, < J_k$. Then, $\forall X \in U, J_q \in R, 1 \leq q \leq k$ lower approximation $\underline{\mathrm{Apr}}(J_q)$, upper approximation $\overline{\mathrm{Apr}}(J_q)$ and boundary interval $Bnd(J_q)$ are determined, respectively, as follows:

$$\underline{\mathrm{Apr}}(J_q) = \cup \{X \in U / R(X) \leq J_q\} \tag{1}$$

$$\overline{\mathrm{Apr}}(J_q) = \mathrm{U}\{X \in U / R(X) \geq J_q\} \tag{2}$$

$$Bnd(J_q) = \cup \{X \in U / R(X) \neq J_q\} = \{X \in U / R(X) > J_q\} \cup \{X \in U / R(X) < J_q\} \tag{3}$$

The object can be demonstrated by rough number (RN) described using lower limit $\underline{Lim}(J_q)$ and upper limit $\overline{Lim}(J_q)$, respectively:

$$\underline{Lim}(J_q) = \frac{1}{M_L}\sum R(X)\Big|X \in \underline{\text{Apr}}(J_q) \quad (4)$$

$$\overline{Lim}(J_q) = \frac{1}{M_U}\sum R(X)\Big|X \in \overline{\text{Apr}}(J_q) \quad (5)$$

where M_L and M_U symbolize the sum of objects included in the lower and upper object approximation of J_q, respectively. The lower limit and upper limit represent the mean value of elements contained in the lower approximation and upper approximation, respectively. Their difference is described as the rough boundary interval ($IRBnd(G_q)$)" (Zhu et al., 2015):

$$IRBnd(G_q) = \overline{Lim}(G_q) - \underline{Lim}(G_q) \quad (6)$$

"Operation for two rough numbers $RN(\alpha) = \left[\underline{Lim}(\alpha), \overline{Lim}(\alpha)\right]$ and $RN(\beta) = \left[\underline{Lim}(\beta), \overline{Lim}(\beta)\right]$:

Addition (+) of two rough numbers (α) and (β)

$$RN(\alpha) + RN(\beta) = \left[\underline{Lim}(\alpha) + \underline{Lim}(\beta), \overline{Lim}(\alpha) + \overline{Lim}(\beta)\right] \quad (7)$$

Subtraction (−) of two rough numbers (α) and (β)

$$RN(\alpha) - RN(\beta) = \left[\underline{Lim}(\alpha) - \overline{Lim}(\beta), \overline{Lim}(\alpha) - \underline{Lim}(\beta)\right] \quad (8)$$

Multiplication (x) of two rough numbers (α) and (β)

$$RN(\alpha) \times RN(\beta) = \left[\underline{Lim}(\alpha) \times \underline{Lim}(\beta), \overline{Lim}(\alpha) \times \overline{Lim}(\beta)\right] \quad (9)$$

Division (÷) of two rough numbers $RN(\alpha)$ and $RN(\beta)$

$$RN(\alpha) \div RN(\beta) = \left[\underline{Lim}(\alpha) \div \overline{Lim}(\beta), \overline{Lim}(\alpha) \div \underline{Lim}(\beta)\right] \quad (10)$$

Scalar multiplication of rough number $RN(\alpha)$, where μ is a nonzero constant" (Vasiljević, Fazlollahtabar, Stević, & Vesković, 2018; Zhai et al., 2008)

$$\mu \times RN(\alpha) = \left[\mu \times \underline{Lim}(\alpha), \mu \times \overline{Lim}(\alpha)\right] \quad (11)$$

"The ranking rule of interval numbers is designated as follows:

1 If the rough boundary interval of a rough number is not strictly bound by another:
   (a) If $\underline{Lim}(\alpha) \geqslant \underline{Lim}(\beta)$ and $\overline{Lim}(\alpha) > \overline{Lim}(\beta)$, or $\underline{Lim}(\alpha) > \underline{Lim}(\beta)$ and $\overline{Lim}(\alpha) \geqslant \overline{Lim}(\beta)$, then $RN(\alpha) > \text{RN}(\beta)$
   (b) If $\underline{Lim}(\alpha) = \underline{Lim}(\beta)$ and $\overline{Lim}(\alpha) = \overline{Lim}(\beta)$, then $RN(\alpha) = \text{RN}(\beta)$
2 If the rough boundary interval of a rough number is strictly bound by another, suppose $M(\alpha)$ and $M(\beta)$ are the middle values of $RN(\alpha)$ and $RN(\beta)$, respectively:
   (a) If $\underline{Lim}(\beta) > \underline{Lim}(\alpha)$ and $\overline{Lim}(\beta) < \overline{Lim}(\alpha)$: if $M(\alpha) \leqslant M(\beta)$, then $RN(\alpha) < RN(\beta)$; if $M(\alpha) > M(\beta)$, then $RN(\alpha) > RN(\beta)$.
   (b) If $\underline{Lim}(\alpha) > \underline{Lim}(\beta)$ and $\overline{Lim}(\alpha) < \overline{Lim}(\beta)$: if $M(\alpha) \leqslant M(\beta)$, then $RN(\alpha) < RN(\beta)$; if $M(\alpha) > M(\beta)$, then $RN(\alpha) > RN(\beta)$" (Zhai et al., 2008; Zhu et al., 2015)

Appendix 2

Step 1. Identify the variables affecting system. A group of q experts was formed, choosing the criteria, and defining the hierarchy of the problem, with the main target at the top and the criteria at the lowest level.

Step 2. Calculate the strength of contextual relationships among factors, which is achieved by collecting expert opinions. By using the scale of relation judgment displayed in Table 3, all q ($p = 1,2, \ldots,q$) experts are asked to rate the strength of the contextual relationship between any two systemic challenges. The relationship matrix of the kth expert is given in D_k Eq. (12).

$$D_k = \begin{bmatrix} 0 & r_{12}^k & \cdots & r_{1m}^k \\ r_{21}^k & 0 & \cdots & r_{2m}^k \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1}^k & r_{m2}^k & \cdots & 0 \end{bmatrix} \quad (12)$$

where r_{ij}^k is the kth expert's judgment value for the ith criterion relationship compared with the jth criterion.

$$\widetilde{D} = \begin{bmatrix} 0 & \widetilde{r}_{12} & \dots & \widetilde{r}_{1m} \\ \widetilde{r}_{21} & 0 & \cdots & \widetilde{r}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{r}_{m1} & \widetilde{r}_{m2} & \cdots & 0 \end{bmatrix} \tag{13}$$

where $\widetilde{r}_{ij} = \{r_{ij}^1, r_{ij}^2, \dots, r_{ij}^q\}$.

Step 3. Convert the element $\widetilde{r}_{ij}$ in group decision matrix $\widetilde{D}$ into rough number form to find rough group decision-making matrix R. Rough number form $\mathrm{RN}(r_{ij}^k)$ of $\widetilde{r}_{ij}$ can be calculated by using Eqs. (1)–(5).

$$\mathrm{RN}\left(r_{ij}^k\right) = \left[r_{ij}^{kL}, r_{ij}^{kU}\right] \tag{14}$$

where r_{ij}^{kL} and r_{ij}^{kU} are the lower limit and upper limit of rough number $\mathrm{RN}(r_{ij}^k)$ in the k th relationship matrix. Thus, we can get rough sequence $\mathrm{RN}(\widetilde{r}_{ij})$,

$$RN(\widetilde{r}_{ij}) = \left\{\left[r_{ij}^{1L}, r_{ij}^{1U}\right], \left[r_{ij}^{2L}, r_{ij}^{2U}\right], \dots, \left[r_{ij}^{qL}, r_{ij}^{qU}\right]\right\} \tag{15}$$

The average rough interval $\overline{RN(\widetilde{r}_{ij})}$ can be achieved by employing rough computation principles Eqs. 7–11:

$$\overline{RN(\widetilde{r}_{ij})} = \left[r_{ij}^L, r_{ij}^U\right] \tag{16}$$

$$r_{ij}^L = \frac{r_{ij}^{1L} + r_{ij}^{2L} + \cdots + r_{ij}^{qL}}{q} \tag{17}$$

$$r_{ij}^U = \frac{r_{ij}^{1U} + r_{ij}^{2U} + \cdots + r_{ij}^{qU}}{q} \tag{18}$$

where r_{ij}^L and r_{ij}^U are the lower limit and the upper limit of the rough number $[r_{ij}^L, r_{ij}^U]$, respectively and, q is the number of experts.

Then, rough group decision matrix R is obtained as follows:

$$R = \begin{bmatrix} 0 & [r_{12}^L, r_{12}^U] & \dots & [r_{1n}^L, r_{1n}^U] \\ [r_{21}^L, r_{21}^U] & 0 & \cdots & [r_{2n}^L, r_{2n}^U] \\ \vdots & \vdots & \ddots & \vdots \\ [r_{n1}^L, r_{n1}^U] & [r_{n2}^L, r_{n2}^U] & \cdots & 0 \end{bmatrix} \tag{19}$$

Step 4. Obtain the aggregated crisp relationship matrix CR, via converting rough numbers into crisp numbers by Eq. (20).

$$d_{ij} = \frac{r_{ij}^L + r_{ij}^U}{2}, \; i = 1, 2, \dots, n \;, \; j = 1, 2, \dots, n. \tag{20}$$

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

Step 5. Build the binary relationship matrix BCR. The binary relationship matrix can be built as follows:

$$BCR = \begin{bmatrix} 0 & \pi_{12} & \cdots & \pi_{1n} \\ \pi_{21} & 0 & \cdots & \pi_{2n} \\ \vdots & \vdots & 0 & \vdots \\ \pi_{n1} & \pi_{n2} & \cdots & 0 \end{bmatrix} \tag{22}$$

$$\pi_{ij} = \begin{cases} 1, \; d_{ij} > d' \\ 0, \; d_{ij} \le d' \end{cases} \tag{23}$$

"Where the parameter d' is a threshold value which is determined by the mean value of crisp relationship matrix of factors; and π_{ij} indicates the relationship between the ith systemic factor and the jth systemic factor" (Kavilal, Prasanna Venkatesan, & Harsh Kumar, 2017; W. Wang et al., 2018).

Step 6. Construct the final reachability matrix as follows:

$$M' = R^{\lambda+1} = R^{\lambda} \neq R^{\lambda-1} \neq \cdots \neq R^2 \neq R \tag{24}$$

"Of which, R is the initial reachability matrix. It is derived by adding the binaryrelationship matrix BCR to the identity matrix I. The parameter M' is the finalreachability matrix, which represents the transitivity of contextual relationships among systemic factors" (Kavilal et al., 2017; W. Wang et al., 2018). The generalized form of M' is denoted as:

$$M' = \begin{bmatrix} \pi'_{11} & \pi'_{12} & \cdots & \pi'_{1n} \\ \pi'_{21} & \pi'_{22} & \cdots & \pi'_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \pi'_{n1} & \pi'_{n2} & \cdots & \pi'_{nn} \end{bmatrix} \tag{25}$$

Step 7. Build an ISM model through the final reachability matrix.

Step 8. Take out the transitive relations from the graph.

Step 9. Investigate the ISM model's conceptual contradictions and, if necessary, make necessary revisions to the model..

Appendix 3

Step 1"Calculate the driving power and dependence power of each factor. Calculations are made by Eqs. (26) and (27):

$$DR\_p_i = \sum\nolimits_{j=1}^{n} \pi'_{ij} \tag{26}$$

$$DE\_p_j = \sum\nolimits_{i=1}^{n} \pi'_{ij} \tag{27}$$

where DR_p_i and DE_p_j symbolize the driving power and dependence power of each factor, respectively. π'_{ij} is the element of final reachability matrix" (W. Wang et al., 2018).

Step 2 Categorize the factors into four clusters by their driving and dependence powers. The four clusters are as follows (Aloini, Dulmin, & Mininno, 2012; Baykasoğlu & Gölcük, 2017):

"*Autonomous factors*: These factors have weak dependence power and weak driving power. Factors belonging to this cluster have few interactions with other factors."

"*Dependent factors*: These factors have weak driving power and strong dependence power. Factors belonging to this cluster have strong dependencies on other factors."

"*Linkage factors*: These factors have strong driving and dependence power. Factors belonging to this cluster have impact on other factors, and they can also be affected by other factors."

"*Driving factors*: These factors have strong driving power but weak dependence power. Factors belonging to this cluster have significant influence on other factors."

Step 3"Identify the most dominant factors. Based on the driving power and dependence power, the concept of the degree of a vertex in a complex network is introduced to recognize the ranking priority of each factor. The degree of a vertex is the number of edges connected to it" (Y. Li, Chu, Chu, & Liu, 2014). The degree of a vertex for each factor in this study can be computed as follows:

$$D_i = DR\_p_i + DE\_p_j\ ,\ i = j \tag{28}$$

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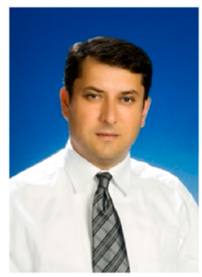

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