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Influential mapping of SDG disclosures based on innovation and knowledge using an integrated decision-making approach

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ABSTRACT

This study addresses the challenges faced by organizations in prioritizing sustainability reporting aligned with the United Nations' Sustainable Development Goals (SDGs). We examine the cause-and-effect relationships among sustainability dimension-related disclosures and specific SDG criteria. This study advocates a prioritization approach to sustainability reporting across sustainability dimensions and SDG reporting criteria. To conduct our empirical analysis, we designate SDG13 (Climate Change), SDG7 (Affordable and Clean Energy), and SDG12 (Responsible Consumption and Production) as representatives of the sustainability dimensions related to the biosphere, society, and economy, respectively. We employ a novel methodology that integrates quantum spherical fuzzy sets (QSFS) into the decision-making trial and evaluation laboratory (DEMATEL) technique. We demonstrate the superiority of our methodology, which enhances the precision of decision-making under uncertainty. Our findings reveal that biosphere disclosure influences the disclosure of the remaining dimensions. Notably, we find that the disclosure criteria for each SDG are interrelated and can be ranked according to the intensity of their influence on each other. Disclosure of "materiality analysis for sustainable energy" is the most influential factor. These findings have managerial implications for future studies. By identifying the interrelations among disclosure criteria and prioritizing the most influential factors, companies can focus their efforts on the most impactful aspects. Our findings provide organizations with a foundation for developing an innovative reporting framework with a prioritization approach to sustainability disclosures. Policymakers can leverage these insights to enhance current reporting practices and contribute to broader discourse on sustainable development.

Introduction

The 2015 United Nations (UN) initiative on Sustainable Development Goals (SDGs) called for a new era of shared responsibility among all societal participants, particularly highlighting the substantial role of the private sector (United Nations, 2015). Scholars emphasize the private sector's commitment to achieving the SDGs as a crucial avenue for advancing corporate social responsibility (CSR) and sustainable development (Bonfanti et al., 2023; García-Sánchez et al., 2020; Suárez Giri & Sánchez Chaparro, 2023; Tu et al., 2023). Aware of the explicit expectation of realigning their strategies with the SDGs, business organizations increasingly rely on sustainability reporting to convey their commitment and contribution to the 2030 agenda.

A growing number of academic studies have explored organizations' involvement in the 2030 agenda, often emanating from sustainability reports (Arena et al., 2023; Hamad et al., 2023; Low et al., 2023; Zampone et al., 2023). Scholars consider SDG disclosures to be associated with, or not different from, voluntary, self-regulated CSR or sustainability reporting practices (e.g., Elalfy et al. 2021). Notably, reporting standards for CSR, such as the Global Reporting Initiative (GRI), integrate SDGs into their frameworks (Elalfy & Weber, 2019). Meanwhile, different international organizations, including the GRI, UN Global Compact, and World Business Council for Sustainable Development (WBCSD), have collaborated to develop reporting frameworks with SDG disclosure criteria to assist businesses in operationalizing SDGs (GRI & UN Global Compact, 2018; GRI et al., 2015; World Business Council for Sustainable Development, 2017).

Developing an effective reporting system requires business organizations to understand the interrelationship between SDG disclosure criteria, a notion that extant studies still need to explore adequately.

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Recent academic inquiries investigate sustainability reporting vis-à-vis disclosure criteria to gauge the organizational achievements related to SDGs (Ferrero-Ferrero et al., 2023; Heras-Saizarbitoria et al., 2022; Manes-Rossi & Nicolo', 2022). However, this line of research examines corporate reporting against specified disclosure criteria in isolation without acknowledging the potential interdependencies among these criteria. Our study aims to bridge this gap in the existing literature by delving into the interrelations and influences of disclosure criteria, particularly within the context of three sustainability dimensions: the biosphere, society, and economy (Rockström & Sukhdev, 2016).

Framed within the perspectives of a multi-theoretical approach to explain voluntary disclosures of CSR activities, legitimacy, stakeholders, and signaling theories, this study examines a prioritization approach to SDG reporting. The objective of this study is to identify the disclosure criteria for the SDGs in separate sustainability dimensions, scrutinize cause-and-effect interactions, and evaluate the intensity of their influence on one another. We investigate the interrelations among disclosure criteria within and across SDG13 (Climate Action), SDG7 (Affordable and Clean Energy), and SDG12 (Responsible Consumption and Production), each representing a sustainability dimension: biosphere, social, and economic, respectively. When selecting each of the three SDGs within each sustainability dimension, we considered their frequency of reporting in corporate sustainability reports and their interrelation with other SDGs. Our analysis incorporates insights from decision science and leverages decision-making and trial evaluation laboratory (DEMATEL) methods. We introduce an innovative approach that incorporates quantum spherical fuzzy sets (QSFS) as an extension of the decision-making framework to enhance decision-making accuracy under uncertainty. The methodology facilitates studying the intensity of the influence of SDG disclosures, aiming to determine whether a reporting framework that prioritizes disclosures along sustainability dimensions could be recommended, with important managerial and theoretical implications.

This study contributes to the literature in two ways. First, while the existing literature on SDG disclosures provides insights into enhancing sustainability commitment, it overlooks the possibility of interrelationships among the disclosure criteria. Kücükgül et al. (2022) proposed an alignment process for existing international reporting guides, providing organizations with an approach to enhance their SDG reporting efforts. García-Sánchez et al. (2022) identified a set of internal and external factors that influence the degree of SDG integration within an organization's overall reporting system. Additionally, Rizzato et al. (2023) emphasize the role of SDG disclosures in determining the level of integrated thinking and reporting efforts, which is essential for the effective implementation of the SDGs (Trucco et al., 2021). Common to these studies is the emphasis on the importance of SDG reporting for an organization's commitment to SDGs. Our primary contribution complements existing research by revealing the interdependencies of disclosures among sustainability dimensions and provides insights into establishing a reporting framework that prioritizes disclosures.

Second, although several studies use fuzzy set theory to examine sustainability issues, none explore the dynamics among disclosures to enhance the reporting process. We extend the literature by proposing a novel approach for constructing a QSFS based on a golden cut, a well-established mathematical concept known for its aesthetic and natural properties. Our study demonstrates that the golden cut approach possesses superior qualities, enhancing the precision of decision-making under uncertainty and overcoming the limitation of determining the correct membership in fuzzy sets. By integrating QSFS into the DEMATEL methodology, we show the applicability and effectiveness of our approach in prioritizing disclosures related to sustainability dimensions and the criteria associated with the SDGs in decision-making processes.

One key finding underscores the significance of biosphere disclosures, which exhibit the highest influence on reporting and serve as a causative factor driving economic and social disclosures. Furthermore, our findings reveal the intricate relationships between the disclosure criteria for each SDG considered in this study. In evaluating the disclosure criteria across the three SDGs, we identify that the disclosure of "materiality analysis for sustainable energy" relating to SDG7 demonstrates the most pronounced intensity of influence. These results provide business organizations with the knowledge needed to prioritize the disclosures that are essential for strategic reporting. The lack of such knowledge prevents effective disclosure of sustainability activities, thereby hindering tangible benefits for various stakeholders (Izzo et al., 2020; Sun et al., 2022; Tsalis et al., 2020).

The remainder of this paper is structured as follows: Section "Theoretical motivation and related literature review" provides the theoretical motivation and related literature review; Section "Research methodology" outlines the research methodology; Section "Empirical findings" incorporates the analysis of empirical findings; Section "Discussion and implications" discusses the results and implications; and finally, Section "Conclusion, limitations, and future research" concludes the paper by emphasizing its contributions and addressing some limitations and future research.

Theoretical motivation and related literature review

In this review, we discuss the theoretical framework for establishing a basis for a prioritization approach to SDG reporting. We draw upon three theories from the literature: legitimacy, stakeholder, and signaling theories. These theories have been widely discussed to explain voluntary CSR disclosure approaches to SDG engagement. We emphasize their relevance to the objectives of this study.

Recently, there has been a dramatic increase in voluntary disclosure of the environmental and social impacts (Pizzi et al., 2021; Silva, 2021). Researchers have adopted stakeholder theory (Freeman, 1984) to explain the substantive approach to SDG reporting. Stakeholder theory views organizations as generating value not only for shareholders but also for various other stakeholders, including the government, civil society, employees, and local communities (Bradford et al., 2017; Chen et al., 2020; Garcia-Sanchez et al., 2014; López-Concepción et al., 2022). This theory posits that companies facing pressure from influential stakeholders are more likely to disclose the demanded information and enhance its quality of disclosed information (García-Sánchez et al., 2020; Jun & Kim, 2021). Emma and Jennifer (2021) demonstrated that SDG reporting on firm performance is higher for firms with increased stakeholder pressure regarding issues related to the biosphere sustainability dimension. García-Sánchez et al. (2023) show that organizations disclose more SDG information relevant to shareholders, focusing on the economic sustainability dimension.

Amid mounting expectations from various stakeholders, business organizations are pressured to enhance the reporting of their CSR activities. According to stakeholder theory, the diverse interests of stakeholders with different concerns regarding sustainability dimensions present a significant challenge for organizations when making reporting decisions (Cho et al., 2015). Stakeholder theory predicts that corporations wishing to address the expectations and interests of individual stakeholder groups should adopt a sustainability reporting approach that prioritizes the disclosure of sustainability dimensions. An effective prioritization approach to sustainability reporting must consider the potential interrelations of sustainability disclosures. By embracing a prioritization approach that not only considers disclosures to an individual stakeholder group, but also examines the cause-and-effect dynamics among sustainability disclosures, organizations can effectively address the diverse interests of stakeholders. Such a reporting system aligns with the predictions of the stakeholder theory and underscores the primary goal of organizations to create shared value by producing positive economic, social, and environmental outcomes.

A prioritization approach to SDG disclosure receives additional support from signaling theory. According to signaling theory, the absence of symmetrical information obliges corporate actors to devise effective actions and policies to communicate with external parties (Connelly et al., 2011; Hahn & Kühnen, 2013). This signaling of sustainability activities becomes particularly relevant as corporate sustainability efforts are not readily available to stakeholders or audited (Cuadrado-Ballesteros et al., 2017; Fernandez-Feijoo et al., 2016; Lyon & Maxwell, 2011). Signaling theory indicates a positive link between sustainability disclosures and an organization's actual performance in terms of sustainability initiatives (Clarkson et al., 2008; Cormier & Magnan, 2007). López-Santamaría et al. (2021) find that companies disclose more SDG information to signal their commitment to stakeholders. Nicolo' et al. (2023) propose that organizations report SDG disclosures when their environmental and social performance is higher to signal their commitment to sustainability. In line with signaling theory, corporations should prioritize their sustainability disclosures to strategically signal their dedication to sustainability initiatives to stakeholders. By carefully selecting disclosure content related to sustainability dimensions, corporations aim to bridge the information gap, enhance transparency, and demonstrate a stronger commitment to sustainability efforts.

Furthermore, legitimacy theory supports the use of a prioritization approach to sustainability reporting. This theory posits that organizations strategically manage their reporting systems to satisfy society's demand for more information to gain legitimacy (Deegan, 2002; Romero et al., 2019). Organizations that disclose activities that do not infringe on social values or protect the environment can secure social licenses (Demuijnck & Fasterling, 2016). Legitimacy theory can explain the reasons for ineffective reporting (Hummel & Schlick, 2016). A particular aspect of the theory is its prediction that firms may proactively manage their reputation or impress a favorable societal perception that they are doing "the right thing" to gain legitimacy.

Several studies have provided empirical evidence of symbolic corporate legitimacy (Avrampou et al., 2019; Izzo et al., 2020; Manes-Rossi & Nicolo', 2022; Van der Waal & Thijssens, 2020; Weerasinghe et al., 2023). A similar pattern is echoed by other researchers, showing that most organizations do not prioritize SDGs based on materiality analysis (Ferrero-Ferrero et al., 2023; Heras-Saizarbitoria et al., 2022). The findings describe the challenge of "cherry-picking," whereby organizations choose relatively easy SDGs to achieve, indicative of a phenomenon described as SDG-washing. The discrepancy between SDG reporting and business activities is consistent with practitioners' views (Mhlanga et al., 2018; PwC, 2019).

Symbolic strategies such as the exaggeration or selective disclosure of CSR activities in sustainability reporting lead to CSR decoupling. CSR decoupling, defined as "the degree of misalignment between a firm's CSR reporting and CSR performance" (Tashman et al., 2019, p. 158), has significant negative implications for firms' financial performance and stakeholder perceptions (Al-Shammari et al., 2022). Even a well-intentioned CSR strategy might not have the desired impact owing to the dynamic and complex manner in which the SDGs relate to one another (Wu et al., 2022). The possible existence of significant divergence implies that disclosed information is associated with "purely ceremonial CSR" (Graafland & Smid, 2019, p. 231). Organizations engaging in CSR decouple risk reputation damage and a subsequent loss of legitimacy once their stakeholders become aware of the misalignment (Al-Shammari et al., 2022).

In alignment with this perspective, the academic literature proposes that organizations manage legitimacy through a substantive rather than a symbolic approach (Boiral, 2013; Michelon et al., 2015). Corporations achieve substantive legitimacy by disclosing information to the public about changes not only in business strategy, but also in business activities (Ashforth & Gibbs, 1990). Substantive corporate legitimacy entails detailed disclosures of the social and environmental dimensions of sustainability that align with societal norms (Romero et al., 2019). Organizations can ensure that disclosures are a meaningful resource (Cho et al., 2015; Deegan, 2019; Hummel & Schlick, 2016). In sustainability reporting, organizations should prioritize disclosure along sustainability dimensions to address societal concerns and values, manage their image, and maintain legitimacy.

In conclusion, adopting a prioritization approach to reporting along sustainability dimensions aligns with the predictions drawn from the three theories discussed: stakeholders, signaling, and legitimacy. By understanding the relationships among sustainability disclosure criteria, corporations can strategically prioritize their reporting efforts, address the diverse needs of stakeholders, signal their commitment to the SDGs, and maintain their legitimacy within a broader societal context.

Research methodology

SDG framework and the choice of SDGs

Griggs et al. (2013) and Rockström and Sukhdev (2016) advocated a unified SDG approach that extends beyond considering sustainability dimensions in isolation. The authors propose placing sustainability goals within a nested framework that envisions interconnectedness among the environmental, social, and economic dimensions. In the context of our study, Rockström and Sukhdev's (2016) model is particularly relevant because it helps conceptualize the interrelations among sustainability dimensions. According to this view, the economic dimension is nested within the societal dimension, which in turn is nested within the Earth's biosphere. This framework positions the biosphere as the largest base dimension with the biggest size, reflecting its priority. Within this model, the SDGs were classified as environmental goals at the base (6, 13−15), social goals in the middle (1−5, 7, 11, and 16), and economic goals at the top (8−10, and 12).

In selecting a specific SDG within each sustainability dimension, we considered the prevalence of reporting in corporate sustainability reports and its interconnectedness with other SDGs. Previous studies that examined corporate SDG reporting identify SDG8, SDG12, and SDG13 (Heras-Saizarbitoria et al., 2022; Jimenez et al., 2021; Monteiro et al., 2023; PwC, 2019; Rizzato et al., 2023) as well as SDG5, SDG7, and SDG8 (García-Sánchez et al., 2023) as widely reported on. Of these SDGs, only SDG13 aligns with the biospheric dimension (Rockström & Sukhdev, 2016). Therefore, we focus on SDG13 (Climate Action) to capture the biosphere dimension. This goal is directly related to the natural system, advocates the urgency of mitigating climate risks, and promotes environmental protection.

We note that SDG5 and SDG7 belong to the social dimension, and SDG8 and SDG12 to the economic dimension. The decision to choose between SDGs 5 and 7 and between SDGs 8 and 12 was informed by the literature on SDG linkage with SDG13. Filho et al. (2023) showed that the SDGs with the most pronounced connection with SDG13 include SDGs 7 and 12, whereas those with the slightest connection include SDG5. Consequently, we select SDG7 (Affordable and Clean Energy) and SDG12 (Responsible Consumption and Production) from the social and economic sustainability dimensions, respectively. SDG7 strives to improve well-being and resilience within societies by emphasizing access to reliable and clean energy sources. On the other hand, SDG12 emphasizes the need for improved sustainable resource management and production practices that focus on protecting natural resources for future generations. Strong interlinkages among SDG13, SDG7, and SDG12 were affirmed by McCollum et al. (2018).

DEMATEL and QSFS methodology

The initial phase of our empirical investigation involved identifying each sustainability dimension's SDG reporting disclosure criteria.

The disclosure criteria were presented to an expert panel, henceforth referred to as decision-makers, to evaluate the interconnectedness of the disclosure criteria. With a minimum of 15 years of experience, decision-makers' backgrounds in reporting and transparency matters, coupled with interdisciplinary knowledge, facilitate impartial and objective decision-making. The evaluations were conducted using webmail services and phone calls. Individual assessments and group discussions are employed to ensure a holistic evaluation, and an iterative feedback loop allows decision-makers to refine their evaluations based on discussions and emerging insights into the criteria and dimensions. This approach aimed to uphold transparency, credibility, and a robust research methodology with the willingness to address further inquiries or engage in additional discussions.

Assessing the intensity of the influence and cause-and-effect relationships among the disclosure criteria is important. Our study leverages DEMATEL, a technique that falls under the broader category of multi-criteria decision-making (MCDM) methods, for rigorous examination. DEMATEL is particularly useful for analyzing complex systems with multiple interrelated factors. The methodology involves creating a matrix to depict the relationships between different criteria and then applying mathematical concepts to prioritize the criteria in decision-making based on their influence and dependence within the system.

In the conventional DEMATEL model, the relationships between criteria are determined as binary outcomes, indicating the presence or absence of an influence. However, this binary conclusion must capture the uncertainties and imprecisions inherent in decision-making processes. Incorporating Fuzzy Set Theory into DEMATEL allows the relationships to be expressed in degrees of strength or influence, as opposed to the rigid existence or non-existence of influence. We chose this methodology carefully because of its distinct advantages in estimating dependencies on sustainability reporting criteria more accurately, especially in situations where the strength of relationships is subject to uncertainties. Furthermore, the use of Fuzzy Set Theory to address sustainability concerns is supported by the literature (Castelló-Sirvent, 2022).

Next, in Section "Quantum spherical fuzzy sets (QSFS) with golden ratio", we elucidate the QSFS, followed by an overview of DEMATEL with QSFS as an extension in Section "Overview of the DEMATEL with QSFS extension".

Quantum spherical fuzzy sets (QSFS) with golden ratio

This Section explains our approach of incorporating DEMATEL with Fuzzy Logic to formulate a sustainability reporting criteria prioritization framework. Fuzzy Set Theory, a mathematical concept extending classical set theory, introduces the notion of "fuzziness" or partial membership. While classical set theory dictates that an element either belongs to a set or does not, fuzzy set theory allows for degrees of membership between zero and one, representing the degree to which an element belongs to a set.

Recently, spherical fuzzy sets have been applied to increase the precision of classical fuzzy set results. Further efficiencies can be achieved when addressing probabilities in decision-making contexts using quantum theory concepts such as amplitude and phase angle. This leads to the concept of the QSFS. Despite these advancements, defining the appropriate membership degrees in Spherical Fuzzy Sets still needs to be addressed in decision-making. To address this issue, the golden ratio is utilized to construct the optimal ratio among the scales of the spherical fuzzy sets, thereby enhancing the accuracy of the QSFS. The details of the QSFS based on the golden ratio are presented in Appendix A.

Overview of the DEMATEL with QSFS extension

We employ DEMATEL with QSFS as an extension to quantify the intensity of influence and analyze the intricate cause-and-effect relationships among sustainability disclosure criteria. We propose a DEMATEL extension in the following six steps: The details are provided in Appendix B.

Step 1: Construct an indirect relationship matrix for the degree of dependency among criteria.

Decision-makers are requested to provide their linguistic evaluations of the degree of influence of the disclosures of each dimension on the disclosures of the other two dimensions. Influence was captured using a defined linguistic scale: no influence, some influence, medium influence, high influence, and very high influence. Linguistic evaluations were conducted to construct the indirect relation matrices. These matrices indicate how the disclosures of each dimension indirectly depend on those of the other dimensions, mapping the interconnections among the disclosures. Consequently, three indirect relation matrices corresponding to the evaluations of the three decision-makers were generated. By applying a consistent methodology, three additional relation matrices for the disclosure criteria related to SDG13, SDG7, and SDG12 were also constructed. This process resulted in the construction of 12 relational matrices.

Step 2: Define the quantum spherical fuzzy direct relation matrices.

Considering each indirect relationship matrix defined in Step 1, we create a matrix that represents the direct relationships between the different disclosures using QSFS, allowing relationships to be represented with uncertainty rather than crisp values (such as 0 or 1). Four QSFS relation matrices were derived, with a matrix at the sustainability dimension level, and three matrices corresponding to SDG13, SDG7, and SDG12, respectively.

Step 3: Defuzzify the quantum spherical fuzzy relation matrices.

This step involves obtaining the QSFS relation matrices and converting the fuzzy values into clear and concrete values. This makes the relationships among disclosures less fuzzy, more precise, and easier to interpret.

Step 4: Normalize the direct relation matrices.

Values inside the direct relation matrices are standardized on a common scale to facilitate a comparison of the degree of directional relationships between disclosure criteria. This ensures a uniform basis for decision-making.

Step 5: Construct the total relation matrices of pairwise influence effects.

This step involves constructing total-relation matrices that capture the total influence effects between any pair of criteria, both directly and indirectly. The total-relation matrices provide a holistic view of the interconnectedness between any pair of criteria.

Step 6: Compute the direction of impact and cause-and-effect relationships.

Each relationship matrix was further analyzed to discern the cause, effect, total effect, weight, and net influence. The values of the elements inside the total relationship matrix, denoted by e_{ij}, measure the influence of the ith criterion on the jth criterion. A significant effect is detected when e_{ij} exceeds the threshold value. The threshold measure is the average of all e_{ij} values within the total relationship matrix. If e_{ij} exceeds this threshold, the criterion in row(i) is considered to affect the criterion in column (j). Given the pairwise relationships depicted in the matrix, every disclosure criterion may influence others or experience the influence of other criteria.

Empirical findings

We present the selected disclosure criteria in Table 1.

Interrelationships among disclosure criteria

The steps described in the DEMATEL-QSFS methodology are as follows. Starting with Step 1, linguistic evaluations are collected from the three decision-makers to construct the relation matrix. Next, we proceed with Steps 2–4 and construct a normalized direct

Table 1
Disclosure criteria.

Disclosure criteria	*Definition*	*Literature*
Panel A: Biosphere dimension: SDG 13: Climate Action (CA)		
Governance disclosure of climate-related risks and opportunities (CA1)	The firm disclosed the oversight role of climate-related risks and opportunities by the board.	FSB (2017)
Business strategy disclosure of climate-related risks (CA2)	The firm disclosed the identification of climate-related risks and opportunities and their impact on business, strategy, and financial statements in the short, medium, and long term, whenever this information is material.	FSB (2017), CDP et al. (2020)
Risk management disclosure of climate-related risks. (CA3)	The firm disclosed its processes on how to identify, assess, and manage climate-related risks.	FSB (2017), CDP et al. (2020)
Disclosure of metrics used to assess climate-related risks. (CA4)	The firm disclosed the metrics used in assessing climate-related risks and published its direct greenhouse gas emissions (Scope 1, Scope 2, and Scope 3)	FSB (2017), IFRS (2020), IOSCO (2021), CDP et al. (2020)
Disclosure of targets to be reached to manage climate-related risks. (CA5)	The firm disclosed its transition plans toward climate-related targets and its performance against such targets.	FSB (2017); CDP et al. (2020)
Panel B: Social dimension: SDG 7: Affordable and Clean Energy (ACE)		
Priority disclosure of the affordable and clean energy goal (ACE1)	The firm disclosed the prioritization of affordable and clean energy targets based on the material impact of its operations and practices across the value chain.	GRI and UN Global Compact (2018), World Business Council for Sustainable Development (2017)
Disclosure of business objectives of the affordable and clean energy goal (ACE2)	The firm disclosed relevant information on how it aligns objectives and strategy to contribute to the affordable and clean energy goal	GRI and UN Global Compact (2018), GRI et al. (2020)
Disclosure of metrics by international standards to assess affordable and clean energy targets (ACE3)	The firm disclosed the international metrics related to the management of energy and energy-related activities when such activities are relevant in the firm sector.	GRI and UN Global Compact (2022)
Disclosure of progress toward the affordable and clean energy target (ACE4)	The firm disclosed its progress against the set objectives for the affordable and clean energy target on a regular basis.	GRI and UN Global Compact (2022)
Panel C: Economic dimension: SDG 12: Responsible Consumption and Production (RCP)		
Disclosure of formal firm policy on sustainable consumption and production pattern. (RCP1).	The firm disclosed the scope and content of its environmental policy that explains the various environmental issues for its activities and operations through the supply chain with consideration of sustainable consumption and production.	Stanwick and Stanwick (2000), GRI and UN Global Compact (2018)
Disclosure of business activities on sustainable consumption and production pattern. (RCP2).	The firm published a sustainability report that discloses relevant information on the actions taken or plans to take toward preventing or remediating along the supply chain the negative impacts associated with the risks of sustainable consumption and production, including waste, food loss, product design, and efficiency in using natural resources.	Lozano (2012), Lozano (2013), GRI and UN Global Compact (2018)
Disclosure of environmental information to engage the various stakeholders, especially consumers. (RCP3).	The firm discloses relevant information to engage the affected stakeholders with sustainable consumption and production, including initiatives that help increase consumer awareness about sustainable consumption and consumer purchase decisions of environmentally friendly products.	GRI and UN Global Compact (2018), Sharma and Rani (2014)
Disclosure of environmental business practices that contribute to sustainable cities and communities. (RCP4).	The firm disclosed business operations relating to energy management and efficiency, waste prevention through reduction, recycling and reuse, product design and lifecycle management, to help make cities and communities inclusive, safe, resilient, and sustainable.	GRI and UN Global Compact (2022)

Table 2
Total relation matrix for disclosures of the sustainability dimensions.

	Biosphere	Society	Economy	Impact directions
Biosphere	129.388	**130.054**	**129.740**	Biosphere → Society, Economy
Society	129.150	129.150	129.169	no influence
Economy	**129.626**	**129.958**	129.311	Economy → Biosphere, Society
Threshold measure	129.505			

relationship matrix for sustainability disclosures. Subsequently, we build the total relation matrix described in Step 5 of the methodology. The results are presented in Tables 2 and 3.

Table 2 shows that disclosures of the sustainability dimensions are related. Disclosures related to the biosphere dimension directly influence both society and economy disclosures. A similar pattern is observed for the economy disclosures. In contrast, disclosures of the social dimension exhibit minimal influence on disclosures of other dimensions. Table 3 reports the directional impact of disclosure criteria on the three representative SDGs within each sustainability dimension.

Table 3
Total relation matrix for disclosures *within* the sustainability dimensions.

Panel A. Disclosures within SDG 13: Climate Action (CA)						
	CA1	CA2	CA3	CA4	CA5	Impact directions
CA1	42.112	**42.293**	**42.279**	**42.429**	**42.339**	CA1→CA2, CA3, CA4, CA5
CA2	42.197	41.978	42.166	42.312	42.223	CA2→CA4
CA3	**42.405**	**42.386**	42.175	**42.525**	**42.432**	CA3→CA1, CA2, CA4, CA5
CA4	42.134	42.115	42.103	42.052	42.162	no influence
CA5	42.183	42.163	42.151	**42.299**	42.010	CA5→CA4
Threshold measure	42.225					
Panel B. Disclosures within SDG 7: Affordable and Clean Energy (ACE)						
	ACE1	ACE2	ACE3	ACE4	Impact directions	
ACE1	27.817	**28.304**	**28.065**	**28.174**	ACE1→ACE2, ACE3, ACE4	
ACE2	27.755	27.737	27.754	27.863	no influence	
ACE3	27.903	**28.134**	27.656	**28.016**	ACE3→ACE2, ACE4	
ACE4	27.796	**28.025**	27.795	27.656	ACE4→ACE2	
Threshold measure	27.903					
Panel C. Disclosures within SDG 12: Responsible Consumption and Production (RCP)						
	RCP1	RCP2	RCP3	RCP4	Impact directions	
RCP1	87.725	87.679	87.438	87.788	no influence	
RCP2	**88.149**	87.600	87.609	**87.958**	RCP2→RCP1, RCP4	
RCP3	**88.321**	**88.024**	87.534	**88.136**	RCP3→RCP1, RCP2, RCP4	
RCP4	**88.091**	87.794	87.555	87.655	RCP4→RCP1	
Threshold measure	87.816					

Table 4
Weights of disclosures of sustainability dimensions.

	r(i) Cause factors	c(j) Effect factors	r(i)+c(j) Total effect	r(i)-c(j) Net effect	Weights	Rankings
Biosphere	389.182	388.164	777.346	1.017	0.3335	1
Society	387.469	389.162	776.631	-1.693	0.3332	3
Economy	388.896	388.220	777.116	0.676	0.3334	2

The findings underscore the interrelationships among the disclosure criteria. Specifically, within the disclosure criteria of SDG13, the disclosures of "board governance of climate risk" (CA1) and "management of climate risk" (CA3) impact all other disclosures. In the case of SDG7, the disclosure of "materiality analysis for sustainable energy," (ACE1) relates to all other criteria. Lastly, the disclosure of "environmental issues to stakeholders about consumption and production initiatives" (RCP3) influences all other disclosure criteria for SDG12. Conversely, the firm's disclosure of "formal firm policy on sustainable consumption and production pattern" (RCP1) depends on every other disclosure criterion and lacks the capacity to influence them.

Intensity of influence (weights) and cause-and-effect relations

Focusing on the reported values in the total relation matrices for the SDG disclosures in Tables 2 and 3, we calculated each criterion's influence and cause-and-effect factors. These findings are reported in Tables 4 and 5. Note that r(i), which is defined as the sum of the influence values of e_{ij} across row i, signifies the influence of criterion i on the other criteria. Conversely, c(j), which is the sum of the values of e_{ij} across column j, indicates the influence of other criteria on criterion j. We interpreted r(i) as the cause and c(j) as the effect of the influencing factors.

The sum r(i)+c(j) captures the total effect of criterion i on the reporting system. The intensity of the influence measures can be computed either "locally" relative to other disclosure criteria within the same SDG or "globally" relative to criteria across all SDGs. The total effect was used to compute both the local and global weights. Local weights are determined by dividing the total effect of a specific criterion (i) by the aggregate total effects of all criteria within the same SDG. Similarly, global weights are calculated by dividing the local weight of a criterion by the sum of the local weights of all criteria across all SDGs. The ranking column in the report provides a hierarchy of disclosure criteria, ordered according to their global weight. Meanwhile, the difference in the

Table 5
Global and local weights of disclosure criteria.

Sustainability dimension	Disclosure criteria	r(i) Cause factors	c(j) Effect factors	r(i)+c(j) Total effect	r(i)-c(j) Net effect	Local weights	Global weights	Rankings
Biosphere	CA1	211.453	211.032	422.485	0.421	0.2001	0.066698	10
	CA2	210.876	210.937	421.812	-0.061	0.1998	0.066598	13
	CA3	211.924	210.874	422.798	1.050	0.2003	0.066764	9
	CA4	210.566	211.618	422.184	-1.051	0.2000	0.066664	11
	CA5	210.806	211.166	421.972	-0.359	0.1999	0.066631	12
Society	ACE1	112.361	111.271	223.632	1.090	0.2505	0.083497	1
	ACE2	111.109	112.200	223.309	-1.091	0.2501	0.083364	5
	ACE3	111.709	111.270	222.979	0.439	0.2497	0.083231	8
	ACE4	111.272	111.709	222.981	-0.437	0.2497	0.083231	7
Economy	RCP1	350.630	352.285	702.915	-1.655	0.2501	0.083364	2
	RCP2	351.316	351.097	702.413	0.219	0.2500	0.083331	4
	RCP3	352.014	350.136	702.149	1.878	0.2499	0.083297	6
	RCP4	351.094	351.537	702.631	-0.442	0.2500	0.083331	3

values of the cause-and-effect factors r(i)−c(j) defines the net influence. A positive net effect indicates a cause criterion, whereas a negative net effect indicates an effect criterion.

Discussion and implications

Discussion

The DEMATEL-QSFS analysis revealed significant interdependencies among the disclosure criteria. Like Muñoz et al. (2008), we use fuzzy logic to address the complexities and subjective elements inherent in sustainability reporting. The approach aligns with the insights from Lassala et al. (2021), who advocate for the use of fuzzy logic to analyze situations wherein "combinations (or configurations) of attributes [may] potentially lead to an outcome." This perspective is particularly relevant to our findings, as shown in Tables 2 and 4. The results indicate that biosphere disclosures have the highest weight, followed by economic and social disclosures. Biosphere disclosures are identified as the most influential in shaping an organization's strategic approach to sustainability reporting.

Biosphere disclosures exhibit strong correlations with other sustainability dimensions, positioning them as causal factors. These biosphere disclosures drive subsequent social and economic disclosures. Disclosures on the economic dimension are of intermediate importance. Additionally, social disclosures depend on disclosures from other sustainability dimensions, with no apparent influence on the remaining disclosures. These social disclosures were categorized as effect factors and were the least influential in our analysis. These results are consistent with theoretical predictions. Within the stakeholder theory, our findings suggest that corporations should prioritize environmental disclosures while considering their causal influence on economic and social dimensions to address the varying objectives of their stakeholders. This approach emphasizes the role of corporations in creating shared value for stakeholders.

The observation that biosphere disclosures trigger subsequent economic disclosures is consistent with the established body of literature examining the economic implications of environmental disclosures, as highlighted by Cormier and Magnan (2015). Previous research indicates that environmental disclosures provide added value for shareholders, particularly those interested in firm profitability (e.g., Clarkson et al. 2004, 2013, Cormier and Magnan 2007). Additionally, a well-strategized CSR approach to corporate social responsibility has been associated with improved financial performance (Husted & De Jesus Salazar, 2006). The evidence collectively suggests that environmental disclosures, when strategically prioritized, contribute positively to a firm's financial health.

We extend the analysis by exploring the direction and intensity of the influence of disclosure criteria within the sustainability dimensions for the three SDGs. The strong relationships among the disclosure criteria within each sustainability dimension are presented in Table 3. A high level of interdependency is depicted in the disclosure criteria of SDG13. This study yielded several observations. None of the climate action disclosure criteria depend on the disclosure of the metric used to assess climate risks (CA4). Though disclosures of "board governance of climate risk" (CA1) and of "management of climate risk" (CA3) exert influence over all other criteria, the latter receives the highest local weight (0.2003), as described in Table 5. This finding corroborates the relevance of risk disclosure in achieving SDG integration into business activities (Manes-Rossi & Nicolo', 2022). Rosati and Faria (2019b) and Pizzi et al. (2021) document the role of environmental risk in positively influencing SDG reporting.

In relation to SDG7, all disclosure criteria correlate with the disclosure of "materiality analysis for sustainable energy" (ACE1). Disclosing the prioritization of this goal based on the material impact of the firm's sustainable energy operations and practices across the value chain directly influences all other disclosure criteria. This disclosure criterion is not subject to external influences. Analyzing the net influence effect in Table 5, we observe a positive value of (+1.090), indicating that the criterion belongs to causal factors. Our analysis highlights that disclosing "materiality analysis for sustainable energy" is the most influential criterion with the highest local weight (0.2505).

The emphasis on the disclosure of "materiality analysis for sustainable energy" (ACE1) corroborates previous findings that organizations lacking a consistent approach to determining their SDG priority may engage in "cherry-picking" (Forestier & Kim, 2020). The theory of substantive approach to legitimacy supports our findings. Disclosing materiality analysis helps stakeholders understand how business organizations identify material issues related to operationalizing the SDGs and how these organizations decide on disclosure content. This analysis is vital for the integration of the SDGs into business activities. Corporations that couple materiality analysis disclosures with serious initiatives to integrate the SDGs in their businesses gain credibility among stakeholders, which is necessary to achieve substantive corporate legitimacy (Boiral, 2013; Silva, 2021).

A similar pattern of interrelationships was observed in the analysis of the SDG 12 disclosure criteria. We found that the criterion for disclosing environmental issues to stakeholders regarding consumption and production initiatives (RCP3) serves as a driving force for the remaining reporting criteria. Importantly, this criterion is not influenced by the other criteria. Our results distinguish between the intensity and direction of the influence of the disclosure criteria. Despite being an essential criterion with the highest local weight (0.2501), disclosure of "formal firm policy on sustainable consumption and production pattern" (RCP1) does not have any influence and can even be influenced by others, as indicated by the negative sign on r(i)-c(j) at (-1.655).

By contrast, the criterion of disclosing "environmental issues to stakeholders about consumption and production initiatives" demonstrates the most significant influence on the other criteria, with the highest positive net effect (+1.878). Previous studies on SDG reporting have underscored the role of disclosure to stakeholders (Jun & Kim, 2021). A common finding is that while quality reporting to stakeholders is essential to integrating the SDGs into core business activities, it often remains of low quality (e.g., Van der Waal and Thijssens 2020) and is primarily directed to shareholders who are keen on the organization's future economic performance (García-Sánchez et al., 2023). Consequently, organizations seeking effective reporting strategies should adopt transparent reporting when communicating with their stakeholders, which will likely enhance other disclosure criteria. Within the context of signaling theory, organizations should report information relating to environmental issues to stakeholders not only to reduce information asymmetry but also to signal sustainability commitment and differentiate themselves from competitors (e.g., Nicolo' et al. 2023).

The interconnectedness of disclosures underscores our methodology for selecting SDGs with robust interlinks (McCollum et al., 2018). In a detailed examination employing fuzzy analysis, Ameli et al. (2023) identified SDGs with strong causal-effect links and interdependence, highlighting SDG13, SDG7, and SDG12. When evaluating the influence of the disclosure criteria across these three SDGs, our analysis revealed that the disclosure of "materiality analysis for sustainable energy" (ACE1) achieved the highest global weight (Table 5), confirming its substantial intensity of influence. The disclosure of materiality analysis in sustainability reports, aiding stakeholders in assessing impact, has been widely acknowledged as crucial in operationalizing the SDGs (e.g., Heras-Saizarbitoria et al. 2022) and gaining substantive legitimacy (Boiral, 2013). These findings extend previous studies on fuzzy analysis that prioritize SDGs but not disclosures (e.g., Ranjbari et al. 2021) and align with those that recognize the relationship between environmental and economic goals, considering their interdependence (Casini et al., 2019; Nomani et al., 2017).

Our findings can serve as a basis for organizations to make informed disclosure decisions. While attending to the needs of various stakeholders for more information, firms should prioritize environmental disclosures within an overall sustainability disclosure narrative while balancing the varying needs arising from promoting environmental, social, and economic objectives. Given their influential characteristics in SDG reporting, organizations should pay particular attention to disclosing information related to the "management of climate risk," "materiality analysis for sustainable energy," and "environmental issues to stakeholders about consumption and production initiatives." Innovative disclosure strategies that consider the interconnectedness between disclosure criteria will help organizations signal their commitment to relevant information to key stakeholders and gain legitimacy.

Implications

Our findings have several theoretical, managerial, and policy implications. A prioritization approach to SDG disclosure has received support from multiple theories. Stakeholder theory uses the perspective of an organization serving various stakeholders, often with divergent interests, to justify the need for a reporting framework that prioritizes disclosures. This approach considers the cause-and-effect relationships detected among sustainability disclosures. The proposed framework aligns with the predictions of signaling and legitimacy theories. Corporations should prioritize disclosure to enhance transparency and signal their commitment to CSR activities. This prioritization distinguishes them from their competitors in the eyes of key stakeholders. By prioritizing disclosures that conform to broader societal norms, organizations safeguard their reputations while maintaining their legitimacy. The evidence of varying levels of influence intensities supports the conjecture that organizations should allocate the necessary resources to develop a prioritization framework for disclosures. From a theoretical perspective, such a framework promises to aid businesses in further integrating SDGs into their strategies while ensuring transparent and valuable disclosures to various stakeholders.

From a managerial perspective, organizations are encouraged to adopt a prioritization approach to SDG reporting that considers the influential capacity of biosphere disclosures. Furthermore, it is prohibitive for organizations to report all disclosure criteria simultaneously. Organizations are encouraged to analyze the interrelationship between disclosure criteria and focus on those with a high intensity of influence on reporting strategy. This knowledge should guide companies to cultivate an innovative reporting framework that prioritizes disclosure criteria. An important implication of our findings is that organizations should give special consideration to disclosures regarding materiality analysis across the value chain of operations. Organizations committed to integrating SDGs into their business strategies and actions should prioritize meaningful materiality analysis while communicating with stakeholders. These practices caution against symbolic approaches to reporting, enhance disclosures, and assist firms in earning substantive legitimacy. On the other hand, policymakers aiming to strengthen sustainability disclosures could reconsider policies to improve disclosures relating to the lower base, the biosphere. The causal effect observed in biosphere disclosures supports the idea that enhancing environmental reporting policies improves reporting across all dimensions. That is, enhanced environmental disclosures will gradually generate a "trickle-up" effect to benefit broader disclosures.

Conclusion, limitations, and future research

Actioning and reporting on SDGs are essential for advancing the UN 2030 Agenda (e.g., Monteiro et al. 2022). Through a comprehensive analysis of SDG business commitments across the world's leading listed companies, Monteiro et al. (2023) reveal substantial disparities in contributions in countries influenced by diverse institutional contexts. This study offers insights into enhancing the commitment of countries lagging in alignment with SDGs. The existing academic literature has examined the complexities related to SDG implementation, highlighting the serious challenges in integrating SDGs into business processes (Hsu, 2023; Jimenez et al., 2021; Li et al., 2023; Santos & Silva Bastos, 2021; Sullivan et al., 2018; Vildåsen, 2018). Obstacles to achieving the SDGs underscore the need for a prioritization approach to disclosure.

To conduct our empirical analysis, we designate SDG13, SDG7, and SDG12 as representatives of the biosphere, social, and economic sustainability dimensions, respectively. After an extensive review of the existing literature, we established a set of disclosure criteria for each selected SDG. Employing the DEMATEL-QSFS methodology, we examined whether business organizations could recommend a prioritization approach to SDG reporting. We contribute to the existing body of knowledge by revealing that disclosures relating to the biosphere dimension have a cause-effect on the disclosures of the social and economic dimensions. This forms the basis of a reporting framework that prioritizes disclosure. Furthermore, upon detecting the interrelations within the disclosure criteria, we identified a unique criterion for each SDGs. Ranking them based on the intensity of influence, the disclosure of "materiality analysis for sustainable energy" emerged as the most influential criterion. These findings aim to assist business organizations in sustainability reporting as they face challenges in operationalizing the SDGs. Our investigation stands out by adopting a novel methodology, thereby adding another valuable contribution to fill the gap in the SDG reporting literature.

Despite their usefulness, these findings should be considered within the limitations of this study. First, we explored the interactions between disclosures for three representative SDGs, each corresponding to a sustainability dimension. This raises concerns that the findings may not be generalizable. Future studies should include a more comprehensive set of SDGs to ensure that the results are consistent with the SDGs considered in this study. Second, while multiple theories predict a framework for disclosure prioritization, the findings should be discussed in the context of institutional theory to explain disclosure behavior (e.g., Subramaniam et al. 2023, Van Zanten and Van Tulder 2018). Future research could draw insights into how institutional factors affect disclosure prioritization. It would be interesting to study disclosure prioritization looks if studied from the perspective of firms under varying institutional pressures in different countries or industries. It is also worthwhile to examine how organizational characteristics such as firm size, stakeholder orientation, and corporate governance factors affect the results.

We call for future research to overcome the identified limitations and deepen our understanding of the intricacies of disclosures of sustainability activities, with particular attention to those related to the biosphere dimension. The theme of the importance of the biosphere as the base layer in the sustainability framework is well captured by Speake (2008), who quotes a Native American saying: "When the last tree is cut, the last fish is caught, and the last river is polluted; when to breathe the air is sickening, you will realize, too late, that wealth is not in bank accounts and that you can't eat money."

Declaration of competing interest

None.

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Appendix A. Quantum spherical fuzzy sets with golden Cut

Quantum mechanics provides a new outlook on information science, decision-making approaches, and the physical issues of real-world problems (Vourdas, 2014; Xiao, 2020). Probability can be considered more efficiently using quantum theory with amplitude and phase angle items. Accordingly, the quantum model of the mass function includes different perspectives for understanding the probabilities of several conditions (Cohen, 2012; Meyer, 1995). Thus, uncertainty can be studied more accurately using a complex information set of quantum logic. The probability of a quantum mass function with amplitude and phase angle has been presented (Dai & Deng, 2020; Gao et al., 2022)

$$Q\left(\Big|u>\right) = \varphi e^{j\theta} \tag{A1}$$

$$\Big|\varsigma> = \left\{\Big|u_1>, \Big|u_2>, \ldots, \Big|u_n>\right\} \tag{A2}$$

$$\sum_{\big|u>\subseteq\big|\varsigma>} \left|Q(\Big|u>)\right| = 1 \tag{A3}$$

ς is the set of collective exhaustive events $|u_i>$, $|Q(|u>)| = \varphi^2$ is the amplitude result for the probability of event $|u>$ in the form of quantum logic. $0 \le \varphi^2 \le 1$ and θ^2 is the phase angle of event $|u>$. $|\varphi_1|^2$ is the belief degree to $|u>$, the value of θ is the phase angle of $|u>$ with the range $[0, 360^0]$.

Decision-making problems generally involve several qualitative and indefinite evaluations that cannot be defined using exact numerical values. This vagueness highlights the need to extend decision-making approaches to provide more accurate results under uncertainty. Fuzzy sets, introduced by Zadeh are one of the most prominent methods for solving the complex problems of decision-making models (Zadeh, 1978). After the introduction of fuzzy logic, some extensions have been presented, such as type 2 and intuitionistic fuzzy sets (Karnik et al., 1999). Recently, Spherical fuzzy sets have been applied to increase the precision of results with generalized forms of Neutrosophic and Pythagorean fuzzy numbers. In this method, the membership, non-membership, and hesitancy degrees of fuzzy numbers are considered together in the decision-making process. A limitation of this extension is that the square sum of the membership, non-membership, and hesitation parameters is between zero and one. The definition of Spherical fuzzy sets $\tilde{A}_S$ is given by the Formulas (4) and (5) (Ashraf et al., 2019; Kutlu Gündoğdu & Kahraman, 2019).

$$\tilde{A}_S = \left\{ \langle u, (\mu_{\tilde{A}_S}(u), v_{\tilde{A}_S}(u), h_{\tilde{A}_S}(u)) \Big| u \in U \right\} \tag{A4}$$

$$0 \le \mu^2_{\tilde{A}_S}(u) + v^2_{\tilde{A}_S}(u) + h^2_{\tilde{A}_S}(u) \le 1, \ \forall_u \in U \tag{A5}$$

The probability of quantum theory can be generalized in the form of spherical fuzzy sets to solve complex decision-making problems with the amplitude and phase angles of the comprehensive set as (Akram & Naz, 2019; Ma et al., 2021).

$$\Big|\varsigma_{\tilde{A}_S}> = \left\{ \langle u, (\varsigma_{\mu_{\tilde{A}_S}}(u), \varsigma_{v_{\tilde{A}_S}}(u), \varsigma_{h_{\tilde{A}_S}}(u)) \Big| u \in 2^{\big|\varsigma_{\tilde{A}_S}>} \right\} \tag{A6}$$

Where, $\varsigma_{\mu_{\tilde{A}_S}}$, $\varsigma_{v_{\tilde{A}_S}}$, and $\varsigma_{h_{\tilde{A}_S}}$ are the membership, non-membership hesitant degrees of Quantum Spherical fuzzy sets, respectively.

However, the Quantum Spherical fuzzy numbers ς are formalized with the amplitude and phase angles of the fuzzy sets.

$$\varsigma = \left[\varsigma_\mu.e^{j2\pi.\alpha}, \varsigma_v.e^{j2\pi.\gamma}, \varsigma_h.e^{j2\pi.\beta}\right] \tag{A7}$$

$$\varphi^2 = \left|\varsigma_\mu\left(\Big|u_i>\right)\right| \tag{A8}$$

where, ς_μ, ς_v, and ς_h are the amplitudes of quantum membership, non-membership, and hesitancy degrees as α, γ, and β are the set of θ phase angles, respectively. φ^2 defines the amplitude of membership function ς_μ of quantum fuzzy sets.

Additionally, defining the right membership, non-membership, and hesitancy degrees in the Spherical fuzzy sets is still an outstanding problem in decision-making methods, and there needs to be a consensus in the determination of membership and other scales. To address this concern, the golden cut can be used to construct the optimal ratio among the scales of the spherical fuzzy sets. Known as the golden ratio, it sheds light on specific patterns of geometry problems. The golden ratio was first studied by Greek mathematicians and later theorists in antiquity to discover the relationship between geometric figures. Previous studies have associated the Fibonacci numbers with the golden ratio (Dunlap, 1997; Livio, 2008). A golden cut is defined by dividing the extreme and mean ratios in a straight line into large and small quantities.

$$G = \frac{a}{b} \tag{A9}$$

where *more significanta* $> b > 0$ and G is the golden cut, a defines a large quantity, and b is a small quantity of the straight line.

The algebraic form of golden cut can also be given as

$$G = \frac{1+\sqrt{5}}{2} = 1.618\ldots \tag{A10}$$

The amplitude of the non-membership degrees for the quantum spherical fuzzy sets was defined with a golden cut using the equation.

$$\varsigma_v = \frac{\varsigma_\mu}{G} \tag{11}$$

The amplitude of hesitancy degrees is presented in the following equation.

$$\varsigma_h = 1 - \varsigma_\mu - \varsigma_v \tag{A12}$$

Accordingly, the phase angles of the quantum spherical fuzzy sets are given as follows:

$$\alpha = \left| \varsigma_\mu \left(\left| u_i > \right) \right| \right. \tag{A13}$$

α is the phase angle of the membership degrees for the probability of event $|u>$ in the form of quantum spherical fuzzy sets.
The phase angle of non-member degrees γ is determined by:

$$\gamma = \frac{\alpha}{G} \tag{A14}$$

The phase angle of hesitancy degrees β is constructed as:

$$\beta = 1 - \alpha - \gamma \tag{A15}$$

X_1 and X_2 are two universes, and $\tilde{A}_\varsigma = (\varsigma_{\mu\tilde{A}} e^{j2\pi.\alpha\tilde{A}}, \varsigma_{v\tilde{A}} e^{j2\pi.\gamma\tilde{A}}, \varsigma_{h\tilde{A}} e^{j2\pi.\beta\tilde{A}})$ and $\tilde{B}_\varsigma = (\varsigma_{\mu\tilde{B}}.e^{j2\pi.\alpha\tilde{B}}, \varsigma_{v\tilde{B}}.e^{j2\pi.\gamma\tilde{B}}, \varsigma_{h\tilde{B}}.e^{j2\pi.\beta\tilde{B}})$ are two quantum spherical fuzzy sets from the universe of discourse X_1 and X_2. The operation of quantum spherical fuzzy numbers is demonstrated by the following equations:

$$\lambda * \tilde{A}_\varsigma = \left\{ \left(1 - \left(1 - {\varsigma_{\mu\tilde{A}}}^2\right)^\lambda\right)^{\frac{1}{2}} e^{j2\pi.\left(1-\left(1-\left(\frac{\alpha\tilde{A}}{2\pi}\right)^2\right)^\lambda\right)^{\frac{1}{2}}},\ {\varsigma_{v\tilde{A}}}^{\lambda} e^{j2\pi.\left(\frac{\gamma\tilde{A}}{2\pi}\right)^\lambda},\ \left(\left(1 - {\varsigma_{h\tilde{A}}}^2\right)^\lambda - \left(1 - {\varsigma_{\mu\tilde{A}}}^2 - \varsigma_{h\tilde{A}}^2\right)^\lambda\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(1-\left(\frac{\beta\tilde{A}}{2\pi}\right)^2\right)^\lambda - \left(1-\left(\frac{\alpha\tilde{A}}{2\pi}\right)^2-\left(\frac{\beta\tilde{A}}{2\pi}\right)^2\right)^\lambda\right)^{\frac{1}{2}}} \right\}, \lambda > 0 \tag{A16}$$

$$\tilde{A}_\varsigma^\lambda = \left\{ {\varsigma_{\mu\tilde{A}}}^\lambda e^{j2\pi.\left(\frac{\alpha\tilde{A}}{2\pi}\right)^\lambda}, \left(1 - \left(1 - {\varsigma_{v\tilde{A}}}^2\right)^\lambda\right)^{\frac{1}{2}} e^{j2\pi.\left(1-\left(1-\left(\frac{\gamma\tilde{A}}{2\pi}\right)^2\right)^\lambda\right)^{\frac{1}{2}}},\ \left(\left(1 - {\varsigma_{v\tilde{A}}}^2\right)^\lambda - \left(1 - {\varsigma_{v\tilde{A}}}^2 - \varsigma_{h\tilde{A}}^2\right)^\lambda\right)^{\frac{1}{2}} e^{j2\pi.\left(\left(1-\left(\frac{\gamma\tilde{A}}{2\pi}\right)^2\right)^\lambda - \left(1-\left(\frac{\gamma\tilde{A}}{2\pi}\right)^2-\left(\frac{\beta\tilde{A}}{2\pi}\right)^2\right)^\lambda\right)^{\frac{1}{2}}} \right\}, \lambda > 0 \tag{A17}$$

$$\tilde{A}_\varsigma \oplus \tilde{B}_\varsigma = \left\{ \begin{array}{l} \left({\varsigma_{\mu\tilde{A}}}^2 + \varsigma_{\mu\tilde{B}}^2 - \varsigma_{\mu\tilde{A}}^2\varsigma_{\mu\tilde{B}}^2\right)^{\frac{1}{2}} e^{j2\pi\cdot\left(\left(\frac{\alpha\tilde{A}}{2\pi}\right)^2+\left(\frac{\alpha\tilde{B}}{2\pi}\right)^2-\left(\frac{\alpha\tilde{A}}{2\pi}\right)^2\left(\frac{\alpha\tilde{B}}{2\pi}\right)^2\right)^{\frac{1}{2}}},\ \varsigma_{v\tilde{A}}\varsigma_{v\tilde{B}} e^{j2\pi\cdot\left(\left(\frac{\gamma\tilde{A}}{2\pi}\right)\left(\frac{\gamma\tilde{B}}{2\pi}\right)\right)}, \\ \left(\left(1 - {\varsigma_{\mu\tilde{B}}}^2\right){\varsigma_{h\tilde{A}}}^2 + \left(1 - {\varsigma_{\mu\tilde{A}}}^2\right)\varsigma_{h\tilde{B}}^2 - \varsigma_{h\tilde{A}}^2\varsigma_{h\tilde{B}}^2\right)^{\frac{1}{2}} e^{j2\pi\cdot\left(\left(1-\left(\frac{\alpha\tilde{B}}{2\pi}\right)^2\right)\left(\frac{\beta\tilde{A}}{2\pi}\right)^2+\left(1-\left(\frac{\alpha\tilde{A}}{2\pi}\right)^2\right)\left(\frac{\beta\tilde{B}}{2\pi}\right)^2-\left(\frac{\beta\tilde{A}}{2\pi}\right)^2\left(\frac{\beta\tilde{B}}{2\pi}\right)^2\right)^{\frac{1}{2}}} \end{array} \right\} \tag{A18}$$

$$\tilde{A}_\varsigma \otimes \tilde{B}_\varsigma = \left\{ \begin{array}{l} \varsigma_{\mu\tilde{A}}\varsigma_{\mu\tilde{B}} e^{j2\pi\cdot\left(\frac{\alpha\tilde{A}}{2\pi}\right)\left(\frac{\alpha\tilde{B}}{2\pi}\right)}, \left({\varsigma_{v\tilde{A}}}^2 + \varsigma_{v\tilde{B}}^2 - \varsigma_{v\tilde{A}}^2\varsigma_{v\tilde{B}}^2\right)^{\frac{1}{2}} e^{j2\pi\cdot\left(\left(\frac{\gamma\tilde{A}}{2\pi}\right)^2+\left(\frac{\gamma\tilde{B}}{2\pi}\right)^2-\left(\frac{\gamma\tilde{A}}{2\pi}\right)^2\left(\frac{\gamma\tilde{B}}{2\pi}\right)^2\right)^{\frac{1}{2}}}, \\ \left(\left(1 - {\varsigma_{v\tilde{B}}}^2\right){\varsigma_{h\tilde{A}}}^2 + \left(1 - {\varsigma_{v\tilde{A}}}^2\right)\varsigma_{h\tilde{B}}^2 - \varsigma_{h\tilde{A}}^2\varsigma_{h\tilde{B}}^2\right)^{\frac{1}{2}} e^{j2\pi\cdot\left(\left(1-\left(\frac{\gamma\tilde{B}}{2\pi}\right)^2\right)\left(\frac{\beta\tilde{A}}{2\pi}\right)^2+\left(1-\left(\frac{\gamma\tilde{A}}{2\pi}\right)^2\right)\left(\frac{\beta\tilde{B}}{2\pi}\right)^2-\left(\frac{\beta\tilde{A}}{2\pi}\right)^2\left(\frac{\beta\tilde{B}}{2\pi}\right)^2\right)^{\frac{1}{2}}} \end{array} \right\} \tag{A19}$$

Appendix B. Overview of the DEMATEL with QSFS extension

The DEMATEL with QSFS extension is explained in the following steps:
Step 1: Construct an indirect relationship matrix for the degree of dependency among criteria.
The linguistic evaluations are collected to construct the indirect relation matrices.

Step 2: Define the quantum spherical fuzzy direct relation matrices.

A quantum spherical fuzzy relation matrix was formulated by considering the indirect relation matrix defined in Step 1: The matrix ς presents the pairwise intensity of influence, ς_{ij}, where i corresponds to the row criterion and j to the column criterion. Matrix is expressed as follows:

$$\varsigma_k = \begin{bmatrix} 0 & \varsigma_{12} & \cdots & \cdots & \varsigma_{1n} \\ \varsigma_{21} & 0 & \cdots & \cdots & \varsigma_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \varsigma_{n1} & \varsigma_{n2} & \cdots & \cdots & 0 \end{bmatrix} \tag{B1}$$

ς_{ij} is defined as $(\varsigma_{\mu_{ij}} e^{2\pi.\alpha_{ij}}, \varsigma_{v_{ij}} e^{2\pi.\gamma_{ij}}, \varsigma_{h_{ij}} e^{2\pi.\beta_{ij}})$, where k is the number of decision-makers. The relation matrices are aggregated across decision-makers. The aggregated values ς of the decision-makers were computed in the form of quantum spherical fuzzy numbers using the following equation:

$$\varsigma = \left\{ \left[1 - \prod_{i=1}^{k}\left(1 - \varsigma_{\mu_i}^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}} e^{2\pi \cdot \left[1 - \prod_{i=1}^{k}\left(1 - \left(\frac{\alpha_i}{2\pi}\right)^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}}, \prod_{i=1}^{k} \varsigma_{v_i}^{\frac{1}{k}} e^{2\pi \cdot \prod_{i=1}^{k}\left(\frac{\gamma_i}{2\pi}\right)^{\frac{1}{k}}}, \right.$$

$$\left. \left[\prod_{i=1}^{k}\left(1 - \varsigma_{\mu_i}^2\right)^{\frac{1}{k}} - \prod_{i=1}^{k}\left(1 - \varsigma_{\mu_i}^2 - \varsigma_{h_i}^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}} e^{2\pi \cdot \left[\prod_{i=1}^{k}\left(1 - \left(\frac{\alpha_i}{2\pi}\right)^2\right)^{\frac{1}{k}} - \prod_{i=1}^{k}\left(1 - \left(\frac{\alpha_i}{2\pi}\right)^2 - \left(\frac{\beta_i}{2\pi}\right)^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}} \right\} \tag{B2}$$

Step 3: Defuzzify the quantum spherical fuzzy relation matrices.

The defuzzified values $Def\,\varsigma$ of Quantum Spherical Fuzzy Sets are computed using the score function:

$$Def\,\varsigma_i = \varsigma_{\mu_i} + \varsigma_{h_i}\left(\frac{\varsigma_{\mu_i}}{\varsigma_{\mu_i} + \varsigma_{v_i}}\right) + \left(\frac{\alpha_i}{2\pi}\right) + \left(\frac{\gamma_i}{2\pi}\right)\left(\frac{\left(\frac{\alpha_i}{2\pi}\right)}{\left(\frac{\alpha_i}{2\pi}\right) + \left(\frac{\beta_i}{2\pi}\right)}\right) \tag{B3}$$

Step 4: Normalize the direct relation matrices.

The normalized direct relationship matrix $B = [b_{ij}]_{n\times n}$ is presented in Eq. (4)

$$B = \frac{\varsigma}{max_{1\le i\le n}\sum_{j=1}^{n}\varsigma_{ij}}\ \text{where},\ 0\le b_{ij}\le 1 \tag{B4}$$

Step 5: Construct the total relation matrices of pairwise influence effects.

The total relation matrix $C = [c_{ij}]_{n\times n}$ is defined as:

$$\lim_{k\to\infty}\left(B + B^2 + \ldots + B^k\right) = B(I - B)^{-1} \tag{B5}$$

Where I is the identity matrix and the total relation matrix provides information about the influence of the ith criterion on the jth criterion, denoted by e_{ij}

Step 6: The total causes and effects are computed. The cause factors r(i) are listed with the sums of the rows, and the effect factors c(j) are the sums of the columns in Eqs. (B6) and (B7).

$$\mathrm{r(i)} = \left[\sum_{j=1}^{n} e_{ij}\right]_{nx1} \tag{B6}$$

$$\mathrm{c(j)} = \left[\sum_{i=1}^{n} e_{ij}\right]_{1xn} \tag{B7}$$

The values r(i) + c(j) indicate the relative importance of the criteria. However, the values of r(i)−c(j) define the direction of the influence of the criteria. The impact-relation directions are represented by using threshold value α as

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left[e_{ij}\right]}{N} \tag{B8}$$

where N is the total number of criteria in matrix. It was assumed that if a criterion in a row had a value higher than the threshold, it affected the criterion of the column in the matrix.

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