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Exploring the mutual influence among the social innovation factors amid the COVID-19 pandemic

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ABSTRACT

From the triple bottom line, the social aspect has received relatively limited attention during the Corona Virus Disease (COVID-19) pandemic, particularly in the emerging economies. Social innovation factors help improve the sustainability performance of the companies. This study develops a social innovation decision framework and analyses the interrelationships among social innovation factors considering the COVID-19 situation. For this purpose, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) is extended by integrating the Z numbers and rough fuzzy set theory into its computational procedure. Z-numbers address the uncertainty of the decision and experts' confidence in the evaluation and rough numbers are used for aggregating the experts' opinions. On this basis, the mutual influence of social innovation factors and the influence weights of these factors are investigated. The results suggest that a quick response to market demand for sustainable products is the most influential factor in attaining social sustainability innovation during the pandemic. This article is concluded by providing insights for industrial experts and decision-makers to understand the underpinnings of social sustainability innovation during unforeseen situations.

1. Introduction

Industrialization has negatively impacted society and nature. Adverse social issues, like poverty, corruption, and human rights along the supply chains are the major obstacles to pursuing sustainable development targets [1]. Governments are introducing stricter measures to enforce sustainability standards in different sectors; following these directives is necessary to materialize the sustainable development goals [2]. Corporations should cooperate to alleviate the negative impact of their activities taking into consideration social, economic, and environmental considerations [3,4]. As one of the major tenets of sustainable development [5], sustainable innovation is of high relevance in adjusting operations to alleviate negative environmental impacts and improve socio-economic and organizational performance; it consists of technological, process, and social innovations for energy saving, waste management, and pollution reduction along supply chains [6].

The Corona Virus Disease (COVID-19) outbreak has impacted business operations and interrupted supply chains [7]. The number of COVID-19 patients is increasing rapidly with the delta and lambda variants taking the death toll and infection rate to over 4.3 and 204.9 million, respectively, as of August 2021. Governments have responded by limiting non-necessary business activities, social distancing, minimizing public gatherings, and canceling indoor events with more than a certain number of participants, among other measures [7]. Lack of raw-material and parts (i.e., chip shortage) and delayed deliveries to the final consumers have been the major consequences of lockdown measures. In this situation, the socio-economic and socio-environmental aspects of businesses have been impacted the most [8]. The pandemic has made decision-makers adjust their supply chain to a more sustainable standard. In particular, the outbreak of COVID-19 has dramatically increased the importance of human health within organizations [9]. Well-informed decisions and initiatives for workplace safety, social distancing, remote working, and health monitoring are much needed to enhance the social aspect of supply chain sustainability in times of pandemic [10].

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For implementing sustainable supply chains, firms must be innovative and responsive to damaging socio-environmental effects. Sustainable innovation includes completely new or developed products, processes and techniques that lead a reduction in harmful socio-environmental effects and improved life quality [11,12] The role of the social dimension of sustainable innovation has received very limited attention in the academic literature; a gap that motivated us to explore the mutual influence among social innovation factors considering the COVID-19 pandemic.

To understand the underpinning of sustainable innovation during disaster situations, there is a need to investigate the influence of COVID-19-related circumstances on social factors. To the best of the authors' knowledge, the mutual influence between the social sustainability innovation factors considering the COVID-19 epidemic situation has not been studied. The outcomes of such analysis show the beneficial and/or detrimental relationships among the factors, which is necessary for suggesting the best course of managerial actions and improving the performance of the sustainability practices. The following research questions are sought to address this research gap:

Q1. Which factors are pertinent for investigating the social dimension of sustainability innovation considering the COVID-19 pandemic?

Q2. How do the interdependencies among social innovation factors impact the decisions?

A twofold contribution is defined to answer these questions. First, a set of decision factors are identified through literature review and interviews with experts to shed light on the social dimension of sustainability innovation decisions during the COVID-19 pandemic. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) can be used to study the interrelationships between the factors pertinent to a decision. The basic DEMATEL is limited in that it cannot address the issue of information uncertainty and ambiguity. Besides, experts' judgments in group decision-making of DEMATEL methods are often integrated using simplistic methods, like simple and weighted averages, which reduces the confidence in the evaluation. Incorporating the Z fuzzy set and rough fuzzy set theories will help overcome these issues in the DEMATEL. As the second contribution, the Rough-Z-DEMATEL technique is proposed to effectively investigate the interdependencies among the social innovation factors during the COVID-19 pandemic situation. Z-numbers reflect the uncertainty and confidence of experts in the evaluation [13], [14] and the opinions of multiple experts can be aggregated using rough numbers [15].

Considering the depth of the COVID-19 catastrophe in the manufacturing sector of the emerging economies, case studies from this scope are used to inform other situations. A visual graph, called Influential Network Relation Map (INRM), is constructed to help improve the decision-making process in similar situations. Overall, the outcomes will help managers to understand the influential relationship among the social innovation factors in the evaluation system and make well-informed decisions and strategies for promoting sustainable innovation in the manufacturing sector. Besides, managerial insights and practical implications are provided for industry practitioners and decision-makers.

The remainder of this manuscript is structured as follows. Section 2 provides a review of the most relevant literature. Section 3 elaborates on the research methodology. Section 4 evaluates the applicability of the proposed model and decision framework using a case illustration. Section 5 presents the discussion of the result. Section 6 presents the practical and theoretical implications of the study. Finally, Section 7 provides the concluding remarks and suggestions for future development in the field.

2. Background

2.1. Sustainable supply chain management

Improving the socio-environmental and socio-economic aspects of supply chains is essential for sustainable development [16]. Social pressures, strict regulations, and the growing public knowledge urge companies to utilize sustainability initiatives in their supply chain operations. In this situation, companies are required to establish a balance between their interests and responsibilities pertinent to social, economic, and environmental issues [17]. As one of the major drivers of sustainable development, Sustainable Supply Chain Management (SSCM) refers to the initiatives that maximize social wellbeing and alleviate negative environmental impacts of the relevant operations [4]; it consists of managing the materials, information, resources, and collaboration between the players within the supply chain taking into consideration social, economic, and environmental considerations [18]. In addition to alleviating the negative impact of supply chain activities, SSCM improves corporates' image and organizational performance [19] and helps establish competitive advantage [20]. A growing number of research papers are addressing SSCM from which, the published works on sustainable innovation are reviewed in the following sub-section.

2.2. Sustainable innovation

Innovation is a prerequisite to achieving sustainable development with maintaining long-term growth being its major pillar [21]. Innovative approaches are much needed for firms to minimize the negative impacts of their activities and pursue sustainability goals [1]. Sustainability innovation can be described as adjusting products and processes to reduce their negative socio-environmental impact [22]; it benefits companies by improving their social image and profitability [23]. Poverty, corruption, health, and safety are prime examples of social challenges that can be addressed through sustainable innovation [24].

Sustainable innovation has implications for social, technological, and cultural aspects of supply chains, which can bring about performance improvement in various organizational and market aspects [25]. The SSCM scholars have long acknowledged that innovation plays a critical role in long-term sustainable development, investigating sustainable innovation in various domains, like in smart product design [26], and end-user sustainable innovation [27], and policymaking [28]. Overall, sustainable innovation consists of social, economic, and environmental aspects [29]; Fig. 1 illustrates the key dimensions of sustainable innovation, which are intertwined and may have overlapped. Social innovation, as the main focus of the present study, is reviewed in the upcoming sub-section.

2.3. Social innovation and COVID-19 pandemic

Social innovations are new ideas with system-changing nature to deal with socio-economic and -environmental aspects and influence people's understanding [30]. In another definition, social innovation is described as novel social practices for dealing with various social challenges [6]; it consists of implementing novel ideas to resolve different socio-environmental issues, improve sustainability, and pursue sustainable development goals [31]. McKelvey and Zaring [32] suggested that social innovation is a major driver for pursuing social changes; it can be implemented in various domains, like commercial, non-profit, and government companies to offer innovative solutions to various socio-environmental problems [33]. Companies can establish a competitive advantage and enhance profitability by creating

Table 1
Social innovation factors.

Factors	Supporting references
Effective communication strategies	[38], [32]
Improving skills	[38], [8]
Cultural and social principles	[39], [40]
Responding to social pressures of stakeholders	[25], [41]
Sharing awareness	[37], [36]
A diversified portfolio of suppliers	[37], [36]
Occupational health and safety	[42], [43]
Localization	[7], [35]
Corporate social responsibility initiatives	[29], [34]
Working in remote situations	[7], [8]
Implementing social and economic initiatives	[44], [25]
Utilizing practical policies considering social indicators	[40], [43]

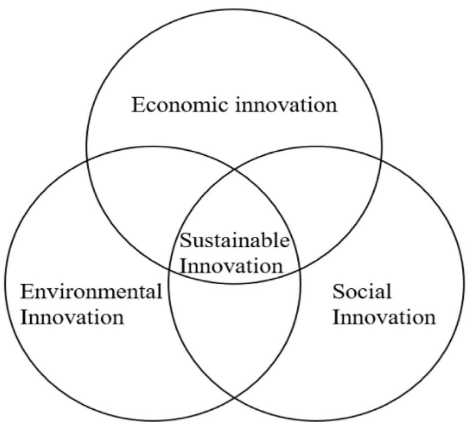

Fig. 1. Dimensions of sustainable innovation.

social values through implementing social innovative practices [34].

The COVID-19 pandemic is, by far, the most disruptive event of the past century. The pandemic has seriously impacted humanity and negatively impacted the world economy and the global market [7,35]. In particular, supply chains have suffered from serious damage to brand image, supply continuity, stakeholder safety, and logistic services, which have resulted in various levels of performance degradation [36]. Arguing that industry experts are concerned the most with the damaging impacts of the COVID-19 situation on business activities and supply chains, Gostin and Wiley [8] noted that companies are confronting challenges pertinent to social and environmental aspects through practical and innovative solutions. In this situation, corporations have employed different social initiatives, like health-related factors, working in remote conditions, skill improvement, and other safety-related measures to reduce the adverse impacts of the pandemic on supply chains [37]. Table 1 summarizes various social innovation factors, including both conventional social innovation considerations, and those pertinent to the COVID-19 pandemic.

2.4. Research gap

Howaldt and Kopp [6] suggested that social innovation should receive more attention relative to technological innovation to deal with social issues. Social innovation has received recent recognition both in the academic literature and practice, with a growing number of scholars investigating the social aspect of sustainability innovation from different perspectives, like cross-country comparison of social innovations for sustainable consumption [45], food provisioning [46], public health [47], universities and social innovation for global sustainable development [48], digital eco-system [49], telecommunication and financial services [50], forestry [51], as well as conceptual studies for general application [52,53]. Studies at the intersection of social innovation, sustainable supply chains, and the COVID-19 pandemic are very limited.

A growing number of studies have shifted their focus on exploring the impact of the pandemic situation on various aspects of SSCM (e.g., [7,54,55]). Fewer studies explored social innovation decision factors at the intersection of supply chain and COVID-19 topics [36]. To the best of the authors' knowledge, the mutual influence among social innovation factors considering the pandemic situation has not been studied. This study extends to address this gap by developing a decision support tool to analyze the interdependencies among social innovation factors, which helps understand the underpinnings of this aspect of sustainable innovation. A detailed description of the developed method is provided in the next section.

3. Research method

This section introduces the Rough-Z-DEMATEL approach. The Rough-Z-DEMATEL improves the adaptability of the basic fuzzy DEMATEL by effective integration of the expert's opinions/judgments and the confidence of experts in the assessment as well as addressing the uncertainty of information [56]. The basic concepts and operators of the Z fuzzy set and rough numbers are first presented. Next, the computational steps of the Rough-Z-DEMATEL approach are detailed. Finally, the Influential Network Relation Map (INRM) is described for the visualization of the interrelationships between the studied factors.

3.1. Z fuzzy set

In group decision-making, the confidence of the decision-makers/experts in the assessment and the uncertainty of information should be taken into consideration. Zadeh [57] proposed Z-numbers as a special type of fuzzy method that measures the confidence of experts in the evaluation. Z-numbers have been widely used in various decision-making problems [13], [14] to address these issues. The computational process of Z-numbers is detailed below.

Step 1. Define the fuzzy system of the evaluation value and confidence. Z-numbers are modeled considering triangular fuzzy triplets. A Z-number can be defined as $Z = \left(\tilde{F}, \tilde{Q}\right) = \left(\left(f^L, f^M, f^U\right), \left(q^L, q^M, q^U\right)\right)$, where $\tilde{F}$ represents the fuzzy membership function of general evaluation, namely $\tilde{F} = \left(f, \mu_{\tilde{F}}\right) \mid y \in [0, 1]$, and $\tilde{Q}$ is the confidence level of the expert in the evaluation that is also a fuzzy membership function denoted by $\tilde{Q} = \left(q, \mu_{\tilde{Q}}\right) \mid y \in [0, 1]$.

Step 2. Convert the fuzzy membership function of confidence to the crisp equivalent. The confidence $\tilde{Q}$ is converted into a crisp value by applying the integral concept shown in Eq. (1). The parameter "φ" denotes the confidence weight.

$$\varphi = \frac{\int^{y} \mu_{\tilde{Q}}\, dy}{\int^{\mu_{\tilde{Q}}} dy}. \tag{1}$$

Step 3. Generate a Z-number. Incorporate the confidence weight φ into the evaluation value $\tilde{F}$ to obtain the weighted Z fuzzy membership function using Eq. (2).

$$Z^{\varphi} = \left\{ \left(y,\ \mu_{\tilde{F}^{\varphi}}\right) \middle| \mu_{\tilde{F}^{\varphi}}(y) = \varphi \mu_{\tilde{F}}(y),\ y \in [0, 1] \right\}. \tag{2}$$

Finally, the weighted Z fuzzy membership function can be converted into a regular triangular fuzzy number using Eq. (3).

$$Z^{*} = \left(\sqrt{\varphi} f^{L}, \sqrt{\varphi} f^{M}, \sqrt{\varphi} f^{U}\right). \tag{3}$$

3.2. Rough numbers

In group decision-making, the alternative rankings/priorities are determined based on multiple experts' integrated subjective assessments. That is, observations/opinions/judgments, the survey data of multiple experts should be integrated in a meaningful way to improve the decision outcomes [15]. Zhai et al. [58] developed rough numbers to construct the upper and lower approximations of a group opinion based on the rough set theory. The implementation process of rough numbers is briefed below.

Step 1. Construct lower and upper approximations. Assuming U as a universe containing all objects with X being a random object from U, there exists a set construct with v classes denoting the expert's preferences, $E = \{K_1, K_2, \ldots, K_v\}$ where $K_1 < K_2 < \ldots < K_v$. In this definition, if $\forall X \in U$, $K_q \in E$, $1 \le q \le v$, two sets $\underline{Apr}\left(K_q\right)$ and $\overline{Apr}\left(K_q\right)$ represent the lower and upper approximations of K_q, which are represented in Eq. (4) and (5), respectively. Besides, the boundary interval, denoted by $Bnd\left(K_q\right)$ can be determined using Eq. (6).

$$\underline{Apr}\left(K_q\right) = \left\{X \in U/E(X) \le K_q\right\}, \text{ the lower approximation;} \tag{4}$$

$$\overline{Apr}\left(K_q\right) = \left\{X \in U/E(X) \ge K_q\right\}, \text{ the upper approximation;} \tag{5}$$

$$\begin{aligned} Bnd\left(K_q\right) &= \left\{X \in U/E(X) \ne K_q\right\} \\ &= \left\{X \in U/E(X) > K_q\right\} \bigcup \left\{X \in U/E(X) < K_q\right\}. \end{aligned} \tag{6}$$

Step 2. Define rough lower and upper limits. The expert opinions can be aggregated using rough numbers with lower and upper limits, i.e. $\underline{Lim}\left(K_q\right)$ and $\overline{Lim}\left(K_q\right)$. These limits are calculated using the arithmetic mean of the elements in the lower and upper approximations shown in Eq. (7) and (8), respectively.

$$\underline{Lim}\left(K_q\right) = \sum_{i=1}^{N_L} E(X)/N_L \left| X \in \underline{Apr}\left(K_q\right)\right.; \tag{7}$$

$$\underline{Lim}\left(K_q\right) = \sum_{i=1}^{N_L} E(X)/N_U \left| X \in \underline{Apr}\left(K_q\right)\right.. \tag{8}$$

where N_L and N_U indicate the total number of objects contained in the lower and upper approximations of K_q, respectively. Notably, the rough boundary, $RBnd\left(K_q\right)$ represents the interval between the upper and lower limits of object K_q, as shown in Eq. (9).

$$RBnd\left(K_q\right) = \overline{Lim}\left(K_q\right) - \underline{Lim}\left(K_q\right). \tag{9}$$

$RBnd\left(K_q\right)$ represents the calculated value of expert consensus, with higher values indicating that there are variations in the experts' opinions while lower $RBnd\left(K_q\right)$ shows that the experts unanimously agree without major conflicts in their judgments.

Step 3. Determine the interval value of rough numbers. As a final step, the opinions of a group of experts should be converted into a set of rough numbers shown in Eq. (10). For a detailed explanation of the calculation of rough numbers, we refer the readers to Chang et al. [59].

$$RN\left(K_q\right) = \left[\underline{Lim}\left(K_q\right), \overline{Lim}\left(K_q\right)\right] \tag{10}$$

3.3. The proposed technique: Rough-Z-DEMATEL

As one of the most popular Multiple Criteria Decision-Making (MCDM) techniques, DEMATEL evaluates the interrelationship between criteria or factors. The outcome of DEMATEL analysis is a structured visual graph, the INRM, which helps decision-makers or experts to understand the direction of influence between the factors [60].

This study extends the DEMATEL technique by integrating (1) Z-numbers to reflect the qualitative information uncertainty and individual confidence of experts in the evaluation; (2) rough set theory to aggregate interview data from multiple experts. Rough-Z-DEMATEL not only improves the coverage of uncertain information but also determines the consensus of a group of decision-makers. We now elaborate on the computational procedure of the Rough-Z-DEMATEL.

Step 1. Prepare the list of social sustainability innovation factors. Invite professional experts on social sustainable innovation to set up an expert group. After group discussion and literature review, the evaluation factors, $F_i = \{F_1,\ F_2, \ldots,\ F_n\}$ are determined.

Step 2. Create the fuzzy membership function of Z-numbers. The Z membership functions across MCDM methods are different. This study adopts the Z-DEMATEL linguistic variables proposed by Hsu et al. [61]. For evaluating the interrelationships between factors, the experts determine the influence of factor i on factor j, (i, $j = 1, 2, \ldots, n$), and assign their confidence in the response. The influence evaluation scale is determined using one of the following linguistic terms: "No Influence (NI)", "Weak Influence (WI)", "Fair Influence (FI)", "Very high Influence (VI)", and "Absolute Influence (AI)". Besides, the five scales of confidence are "Very Low (VL)", "Low (L)", "Moderate (M)", "High (H)", and "Very High (VH)". For example, an expert's response to assessing an event is "weak influence and moderate confidence". It can be recorded as {WI, M}. That is, the corresponding Z membership function is (0.000, 0.707, 1.414). Given a total of 25 combinations of linguistic terms, the Z fuzzy membership function corresponding to the linguistic variable of each combination is provided in Table 2.

Step 3. Establish the z direct influence matrix for each expert. The experts use the linguistic variables in Table 2 to construct a direct influence matrix, as shown in Eq. (11).

$$\otimes \boldsymbol{D}^{(k)} = \left[\otimes d_{ij}^{(k)}\right]_{n\times n} = \begin{bmatrix} \otimes d_{11}^{(k)} & \otimes d_{12}^{(k)} & \cdots & \otimes d_{1n}^{(k)} \\ \otimes d_{21}^{(k)} & \otimes d_{22}^{(k)} & \cdots & \otimes d_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes d_{n1}^{(k)} & \otimes d_{n2}^{(k)} & \cdots & \otimes d_{nn}^{(k)} \end{bmatrix}_{n\times n}. \tag{11}$$

where $\otimes d_{ij}^{(k)} = \left(d_{ij}^{(k),L},\ d_{ij}^{(k),M},\ d_{ij}^{(k),U}\right)$ represents a Z-number. It is worthwhile noting that the diagonal elements in the matrix are 0 (i.e., there is no self-influence); that is, $\otimes d_{ii}^{(k)} = 0$ when $i = j$.

Step 4. Defuzzying the elements of z direct influence matrix. Eq. (12) is used to defuzzify the elements in the direct relationship matrix.

$$d_{ij}^{(k)} = \frac{\left(d_{ij}^{(k),L} + 2 \cdot d_{ij}^{(k),M} + d_{ij}^{(k),U}\right)}{4}. \tag{12}$$

Table 2
The linguistic variables and Z membership functions [61].

		Confidence				
		VL	L	M	H	VH
Influence	*NI*	(0.000, 0.000, 0.316)	(0.000, 0.000, 0.548)	(0.000, 0.000, 0.707)	(0.000, 0.000, 0.837)	(0.000, 0.000, 0.949)
	WI	(0.000, 0.316, 0.632)	(0.000, 0.548, 1.096)	(0.000, 0.707, 1.414)	(0.000, 0.837, 1.673)	(0.000, 0.949, 1.897)
	FI	(0.316, 0.632, 0.949)	(0.548, 1.096, 1.644)	(0.707, 1.414, 2.121)	(0.837, 1.673, 2.510)	(0.949, 1.897, 2.846)
	VI	(0.632, 0.949, 1.265)	(1.096, 1.644, 2.192)	(1.414, 2.121, 2.828)	(1.673, 2.510, 3.347)	(1.897, 2.846, 3.795)
	AI	(0.949, 1.265, 1.265)	(1.644, 2.192, 2.192)	(2.121, 2.828, 2.828)	(2.510, 3.347, 3.347)	(2.846, 3.795, 3.795)

Step 5. Generate the rough direct influence matrix. Applying the calculation process of rough numbers in Section 3.2, the direct influence matrix from the experts is integrated into one rough direct influence matrix shown in Eq. (13).

$$RN(\boldsymbol{D}) = \left[RN\left(d_{ij}\right)\right]_{n\times n} = \begin{bmatrix} RN(d_{11}) & RN(d_{12}) & \cdots & RN(d_{1n}) \\ RN(d_{21}) & RN(d_{22}) & \cdots & RN(d_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ RN(d_{n1}) & RN(d_{n2}) & \cdots & RN(d_{nn}) \end{bmatrix}_{n\times n}. \tag{13}$$

where $RN\left(d_{ij}\right) = \left[\underline{Lim}\left(d_{ij}\right), \overline{Lim}\left(d_{ij}\right)\right]$ and symbol "*RN*" represents a rough number.

Step 6. Calculate the normalized rough direct relation matrix. Eq. (14) is used to normalize the rough direct influence matrix.

$$RN(\boldsymbol{A}) = \left[RN\left(a_{ij}\right)\right]_{n\times n} = \begin{bmatrix} \rho\cdot RN(d_{11}) & \rho\cdot RN(d_{12}) & \cdots & \rho\cdot RN(d_{1n}) \\ \rho\cdot RN(d_{21}) & \rho\cdot RN(d_{22}) & \cdots & \rho\cdot RN(d_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ \rho\cdot RN(d_{n1}) & \rho\cdot RN(d_{n2}) & \cdots & \rho\cdot RN(d_{nn}) \end{bmatrix}_{n\times n} \tag{14}$$

where $RN\left(a_{ij}\right) = \left[\underline{Lim}\left(a_{ij}\right), \overline{Lim}\left(a_{ij}\right)\right]$, and $\rho = \min\left\{\frac{1}{\max_i \sum_{j=1}^{n} \overline{Lim}(a_{ij})}, \frac{1}{\max_j \sum_{i=1}^{n} \overline{Lim}(a_{ij})}\right\}$.

Step 7. Obtain the rough total influence matrix. The rough total influence matrix is raised to an infinite power, as shown in Eq. (15) to estimate the total influence between the factors, which consists of direct and indirect relationships. Eq. (15) is derived from Eq. (16) as a simplified calculation formula.

$$RN(\boldsymbol{T}) = RN(\boldsymbol{A}) + RN(\boldsymbol{A})^2 + \cdots + RN(\boldsymbol{A})^{\infty} \tag{15}$$

$$\begin{aligned} RN(\boldsymbol{A}) &= RN(\boldsymbol{A}) + RN(\boldsymbol{A})^2 + \cdots + RN(\boldsymbol{A})^{\infty} \\ &= RN(\boldsymbol{A})\left(\boldsymbol{I} + RN(\boldsymbol{A}) + RN(\boldsymbol{A})^2 + \cdots + RN(\boldsymbol{A})^{\infty-1}\right) \\ &= RN(\boldsymbol{A})\left(\boldsymbol{I} - RN(\boldsymbol{A})^{\infty}\right)(\boldsymbol{I} - RN(\boldsymbol{A}))^{-1} \\ &= RN(\boldsymbol{A})(\boldsymbol{I} - RN(\boldsymbol{A}))^{-1} \end{aligned} \tag{16}$$

where $RN(\boldsymbol{A})^{\infty} = [0]_{n\times n}$ and "$\boldsymbol{I}$" denotes the Identity matrix, which is a zero matrix with diagonal values of 1.

Step 8. Plot INRM to visualize the influential relationship among the factors. The degree of rough affecting relationship ($RN(R_i)$) and the degree of rough affected relationship ($RN(C_j)$) can be obtained by adding up the rough total influence matrix of every row and column, respectively, as shown in Eqs. (17)–(18).

$$\left[RN(R_i)\right]_{n\times 1} = \left[\sum_{j=1}^{n} RN\left(t_{ij}\right)\right]_{n\times 1}, \tag{17}$$

$$\left[RN\left(C_j\right)\right]_{1\times n} = \left[\sum_{i=1}^{n} RN\left(t_{ij}\right)\right]_{1\times n} = \left[RN(C_i)\right]^{T}_{n\times 1}. \tag{18}$$

where $RN(R_i) = \left[\underline{Lim}(R_i), \overline{Lim}(R_i)\right]$ and $RN(C_i) = \left[\underline{Lim}(C_i), \overline{Lim}(C_i)\right]$. On this basis, Eqs. (19)–(20) are used to convert the rough numbers into crisp equivalents denoted by R_i and C_i.

$$R_i = \frac{\left(\underline{Lim}(R_i) + \overline{Lim}(R_i)\right)}{2} \tag{19}$$

$$C_i = \frac{\left(\underline{Lim}(C_i) + \overline{Lim}(C_i)\right)}{2} \tag{20}$$

Finally, R_i + C_i expresses the strength of total influences, comprising dispatched and received. Larger values of "R_i + C_i" for a factor determine its high significance in the evaluation system. Therefore, the influence weights of the factors can be obtained using Eq. (21).

$$w_i = \frac{(R_i + C_i)}{\sum_{i=1}^{n}(R_i + C_i)} \tag{21}$$

On the other hand, R_i - C_i can be used to determine the net influence of the factor. Given R_i + C_i and R_i + C_i as the measures on the horizontal and vertical axis, respectively, the coordinates of each factor determine its position on INRM. Besides, arrows are used to show the direction of significant influence amongst every pair of the factors.

4. Case application and results

4.1. Case background

Inputs from a developing country in the Middle East are used to explore the mutual influence among the social innovation factors during the COVID-19 pandemic. Social sustainability development in Iran's manufacturing sector is at its initial stages and needs more investment and investigation [62]. For achieving the research objectives, seven managers from seven different Iranian manufacturing firms were selected as our experts to participate in this study and help in the assessment process. Each of these experts has more than 10 years of working experience. The experts are purposely selected from different backgrounds for gaining homogeneity and ensuring that the results can be generalized and inform other industry situations. According to Rezaei et al. [63], expert-based methodologies can rely on a small sample of experts, like in Gupta and Barua [5] and Moktadir et al. [64]. Table 3 summarizes the expert profiles.

4.2. The assessment framework

Given the social innovation factors in Table 1, a survey was designed and submitted to the experts to determine whether these factors are perceived as relevant in their company's supply chains; (Yes) for accepted, or (No) for rejected. Besides, they were asked to suggest additional social innovation factors that are perceived as relevant according to their experience. After approving

Table 3
Profile of the experts involved in this study.

Expert	Position	Experience (Years)	Industry
1	Supply manager	15	Leather manufacturing firm
2	Production manager	16	Steel manufacturing firm
3	Financial manager	17	Automobile firm
4	General manager	12	Electronic firm
5	Purchasing manager	11	Tile firm
6	Assistant supply manager	15	Plastic firm
7	Marketing manager	18	Motorcycle firm

the factors list by at least five experts, it was sent back to the experts for the next round of review, and they were requested to revise their first response if necessary. On this basis, '*Rights of the employees*' and '*Quick response to market demand for sustainable products*' were suggested by two of the decision-makers. After three rounds of reviews, eight factors were selected for the final evaluation, as explained in Table 4. This screening approach has been widely applied to determine whether a particular factor should be included in the final assessment [65].

4.3. Application of Rough-Z-DEMATEL

The experts were invited to assess the mutual influence of factors using the linguistic terms from Table 2. The input from Expert 1 is presented in Table 5 as an example. Following the Z-numbers conversion approach proposed by Hsu et al. [61], the elements of Table 5 are then converted to Z membership function equivalents shown in Table 6. Finally, the defuzzification procedure is applied to the Z membership functions to obtain the crisp direct influence matrix of Expert 1, as shown in Table 7. At the pre-processing stage, the uncertainty and confidence of all experts are considered in the assessment.

MCDM studies predominantly use simplistic methods, like simple and weighted averages to integrate group judgments. This approach is limited in that it may cause missing parts of the information. For example, even if an expert expresses extreme opinions, it can be ignored when the average method is used. The concept of rough set theory is applied to address this issue. Table 8 shows the outcome that is used to construct the lower and upper approximations of the group. In so doing, the consensus of experts can be subtracted from the upper approximation by the lower approximation. For example, the rough direct influence of F1 on F2 is [1.682, 1.792] and the consensus degree in this judgment amounts to 0.11. Given the maximum and minimum values in Table 2, the consensus degree ranges from 0 to 3.795.

After completing the computational process of Rough-Z-DEMATEL, the influence weights are obtained and the INRM is constructed considering the prominence (R_i + C_i), and net-causation (R_i - C_i) values. According to Table 9, F6 has the highest influence weight, which is 0.135. There is no significant difference in the weight of the rest of the factors because they have a strong mutual influence. The INRM of the factors is presented in Fig. 2 followed by a discussion of the results provided in Section 5.

5. Discussions

The resulting ranking of social sustainability innovation factors is F6 > F7 > F8 > F3 > F5 > F4 > F1 > F2; "Quick response to market demand for sustainable products (F6)" received the highest ranking in the analysis, hence, can be regarded as the most influential factor for attaining social sustainability innovation. Previous studies suggested that corporations should develop effective strategies and consider a variety of social standards while responding to market demands [11]. Particularly in highly uncertain situations, like the COVID-19 pandemic, applying effective social standards plays a significant role in maintaining the sustainability and competitiveness of the corporations [25]. This is in line with our findings from the Rough-Z-DEMATEL analysis where "Quick response to market demand for sustainable products" shows the highest prominence. Industrial experts and decision-makers in emerging economies should prioritize this factor to pursue social sustainability innovation during and after the COVID-19 pandemic.

The next important social sustainability innovation factor appears to be 'Working in remote situations (F7)' considering the prominence ranking. During the COVID-19 pandemic, most of the employees are working from home, some of which may face technical issues related to infrastructure and bandwidth ability and limitations, like living with families in a small home with limited facilities. Employers need to understand the situation of the employees and provide them with the necessary support and solutions to their problems to ensure that they are more effectively engaged in work and can stay productive. Besides, working from home may become a norm for certain industries. The results are in line with the findings of Gostin and Wiley [8] who also indicate that employers need to focus on the working conditions of their employees during the time of the pandemic.

The third important factor as per the prominence ranking is 'Localization (F8)'. The pandemic has caused disruptions all over the world and impacted the logistics sector the most with production schedules being delayed for many organizations. Besides, many small- and medium-size organizations have been forced to close down or limit their operations, causing job losses. To overcome the impact of disruptions caused by the major disruptive events, like pandemics, organizations need to be more supportive of local companies and products, while organizations need to source more products and raw materials from local suppliers and small businesses, which in turn improves employment opportunities for locals [7,66].

The 'Cultural and social principles (F3)' is the next important social innovation factor. Organizations all over the world are disrupted due to the pandemic while their employees' well-being and productivity are also in jeopardy. Organizations need to develop and re-assess their cultural and social values and principles to deal with changing situations. Managers should focus on developing transparency and open communication within the organizations and creativity among employees to enhance problem-solving capabilities. Besides, they should establish a collaborative work environment for engaging employees at all functional levels for developing solutions to the problems the company faces. Overall, developing a culture that value and promote innovation in the organizations encourages employees to come up with novel solutions to deal with the disruptions caused due to pandemic. Recent studies, like [39] and [40] support the idea that organizations need to focus on their cultural and social values for supporting social sustainable innovations for dealing with the impacts of the pandemic.

Analyzing the INRM graph in Fig. 2, one can conclude that the social sustainability innovation factors 'Quick response to market demand for sustainable products (F6)', 'Working in remote situations (F7)', 'Localization (F8)', 'Rights of the employees (F5)' and 'Improving skills (F4)' have emerged as cause group factors (i.e., the influencers). From the cause group factors, 'Quick response to market demand for sustainable products (F6)' has the highest influence in the network, which is also indicated by the prominence ranking. It is also observed that F6 influences every other social innovation factor. In this context, timely response to the customer demands and knowing about sustainable products influences localization. As organizations aspire to quickly meet

Table 4
Factors in the proposed framework.

Factors	Explanation
Utilizing practical policies considering social indicators (F1)	This relates to the utilization of strategies, procedures, and programs that gain the commitment of the involved parties, employees, and are necessary to address the social considerations in the work place and beyond.
Effective communication strategies (F2)	Providing the personel with clear, correct, and timely updates on the situation, including the changes that may impact them and provide helps for dealing with the changes.
Cultural and social principles (F3)	The cultural and social values within a company determine the way the employees behave in unprecedented conditions; adjusting such values facilitate organizational sustainability and resilience.
Improving skills (F4)	Improving the workforce skills and preparing them to better deal with the challenges in turbulent situations.
Rights of the employees (F5)	Workforce rights at the workplace and improving the working conditions sustainably.
Quick response to market demand for sustainable products (F6)	Developing knowledge about the market dynamics, timely response to demand changes, and introducing sustainable products/services.
Working in remote situations (F7)	Understanding the workforce issues related to remote working conditions during the COVID-19 outbreak; this includes soft and hard factors that impact the health, wellness, and productivity of the employees.
Localization (F8)	Offering more opportunities to locals and more reliance on the native capacity.

Table 5
The Z direct influence matrix of Expert 1 (linguistic terms).

	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	(FI, H)	(FI, H)	(VI, M)	(FI, M)	(VI, H)	(FI, H)	(FI, H)
F2	(VI, H)	0	(VI, H)	(WI, M)	(FI, M)	(FI, H)	(WI, M)	(WI, H)
F3	(FI, VH)	(WI, M)	0	(NI, M)	(WI, VH)	(WI, VH)	(NI, H)	(WI, H)
F4	(VI, M)	(FI, M)	(VI, M)	0	(VI, VH)	(WI, VH)	(NI, M)	(VI, VH)
F5	(WI, M)	(NI, VH)	(WI, H)	(FI, VH)	0	(NI, M)	(VI, VH)	(VI, VH)
F6	(NI, H)	(VI, VH)	(FI, H)	(VI, H)	(VI, H)	0	(VI, VH)	(FI, VH)
F7	(VI, H)	(VI, VH)	(NI, VH)	(AI, H)	(AI, H)	(VI, M)	0	(NI, H)
F8	(WI, VH)	(WI, H)	(WI, VH)	(VI, H)	(WI, H)	(AI, VH)	(AI, H)	0

Table 6
The Z direct influence matrix of Expert 1 (Z membership functions).

	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	(0.837, 1.673, 2.510)	(0.837, 1.673, 2.510)	(1.414, 2.121, 2.828)	(0.707, 1.414, 2.121)	(1.673, 2.510, 3.347)	(0.837, 1.673, 2.510)	(0.837, 1.673, 2.510)
F2	(1.673, 2.510, 3.347)	0	(1.673, 2.510, 3.347)	(0.000, 0.707, 1.414)	(0.707, 1.414, 2.121)	(0.837, 1.673, 2.510)	(0.000, 0.707, 1.414)	(0.000, 0.837, 1.673)
F3	(0.949, 1.897, 2.846)	(0.000, 0.707, 1.414)	0	(0.000, 0.000, 0.707)	(0.000, 0.949, 1.897)	(0.000, 0.949, 1.897)	(0.000, 0.000, 0.837)	(0.000, 0.837, 1.673)
F4	(1.414, 2.121, 2.828)	(0.707, 1.414, 2.121)	(1.414, 2.121, 2.828)	0	(1.897, 2.846, 3.795)	(0.000, 0.949, 1.897)	(0.000, 0.000, 0.707)	(1.897, 2.846, 3.795)
F5	(0.000, 0.707, 1.414)	(0.000, 0.000, 0.949)	(0.000, 0.837, 1.673)	(0.949, 1.897, 2.846)	0	(0.000, 0.000, 0.707)	(1.897, 2.846, 3.795)	(1.897, 2.846, 3.795)
F6	(0.000, 0.000, 0.837)	(1.897, 2.846, 3.795)	(0.837, 1.673, 2.510)	(1.673, 2.510, 3.347)	(1.673, 2.510, 3.347)	0	(1.897, 2.846, 3.795)	(0.949, 1.897, 2.846)
F7	(1.673, 2.510, 3.347)	(1.897, 2.846, 3.795)	(0.000, 0.000, 0.949)	(2.510, 3.347, 3.347)	(2.510, 3.347, 3.347)	(1.414, 2.121, 2.828)	0	(0.000, 0.000, 0.837)
F8	(0.000, 0.949, 1.897)	(0.000, 0.837, 1.673)	(0.000, 0.949, 1.897)	(1.673, 2.510, 3.347)	(0.000, 0.837, 1.673)	(2.846, 3.795, 3.795)	(2.510, 3.347, 3.347)	0

customer demand during the pandemic, they need to focus on developing more local sources for their product raw material and assemblies. These considerations together help enhance localization and offer employment opportunities to locals. F6 also strongly influences 'Cultural and social principles (F3)', 'Improving skills (F4)' and 'Utilizing practical policies considering social indicators (F1)'. For the companies to respond quickly to the market changes, organizations should have a culture of open communication about the work that needs to be done in a certain time frame; this helps develop innovative solutions to meet the deadlines in the volatile scenario caused by the pandemic and other similar events. Besides, for adopting environmentally sustainable products and being responsive to customer needs during the time of the pandemic, organizations are encouraged to provide training to their employees to enhance their skills to meet the organizations' goals during the pandemic. Devising policies

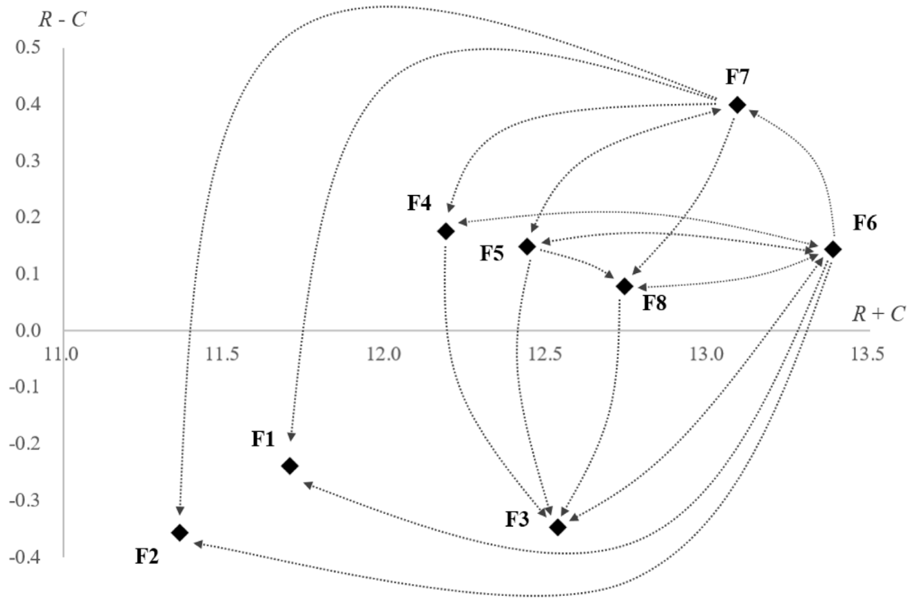

Fig. 2. The influential network relation map of the factors.

Table 7
The crisp direct influence matrix of Expert 1 (defuzzification results).

	F1	F2	F3	F4	F5	F6	F7	F8
F1	0	1.673	1.673	2.121	1.414	2.510	1.673	1.673
F2	2.510	0	2.510	0.707	1.414	1.673	0.707	0.837
F3	1.897	0.707	0	0.177	0.949	0.949	0.209	0.837
F4	2.121	1.414	2.121	0	2.846	0.949	0.177	2.846
F5	0.707	0.237	0.837	1.897	0	0.177	2.846	2.846
F6	0.209	2.846	1.673	2.510	2.510	0	2.846	1.897
F7	2.510	2.846	0.237	3.138	3.138	2.121	0	0.209
F8	0.949	0.837	0.949	2.510	0.837	3.558	3.138	0

and social sustainability initiatives are required to compete with other organizations during this volatile period, which emphasizes responsiveness and the launch of sustainable products during the pandemic as indicated by the interrelationship analysis.

The interrelationship analysis also revealed that 'Working in remote situations (F7)' has a significant influence on some other factors like 'Improving skills (F4)', 'Effective communication strategies (F2)', 'Utilizing practical policies considering social indicators (F1)', 'Rights of the employees (F5)', and 'Localization (F8)'.

Four DEMATEL-based method comparisons, including original DEMATEL, triangular fuzzy DEMATEL, Z-DEMATEL, and Rough-Z-DEMATEL (our model) are considered to study the methodological implication of the proposed method. The first method is the classic DEMATEL, where the evaluation scale is from 0 to 4 to measure the interrelationship amongst the criteria. The second method is triangular fuzzy DEMATEL, which introduces triangular fuzzy numbers into DEMATEL to reflect information uncertainty. Z-DEMATEL is the third method, extending the concept of triangular fuzzy DEMATEL, which takes into account the confidence of experts in the evaluation. The last variant is the Rough-Z-DEMATEL technique, which is proposed in this paper. Table 10 and Fig. 2 present the criteria weights and rankings for the four DEMATEL methods. The first two methods are not identical to the results of the proposed Rough-Z-DEMATEL analysis. Furthermore, although the results of Z-DEMATEL are similar to the proposed model, we consider the integration of various expert opinions, individual expert's confidence and his or her uncertainty. Table 11 summarizes a description of the differences between the four methods (see Fig. 3).

6. Implications

6.1. Practical implications

Given the limitations around working from home and the importance of providing technical support and infrastructure, having more employees working from remote locations influences an organization's ability to source raw materials and sub-assemblies of their products from local sources; in doing so, the limitations related to the workforce can be alleviated and the market demand can be fulfilled in a timely fashion. In a post-pandemic world, the work-from-home experience opens up new cost-saving opportunities, support for less advantaged communities, and inclusion of vulnerable groups and people with special needs and disabilities. This requires organizations to provide training to their employees so that they can work from remote locations more effectively and efficiently considering available resources and without stress-induced because of the pandemic-like situations. Organizations are required to come up with policies for effective communication among employees working from different locations so that organization's sustainability-related goals can be met effectively. Effective communication among employees helps them to come up with innovative and sustainable ideas for the problems and challenges that emerge due to pandemics. Finally, working from home as a paradigm shift requires fresh policies and law/regulatory frameworks to fully benefit from its advantages. The managers should also be cognizant of the fact that some workers can be more productive at home, and that an optimal combination of working from home and at the office in the post-pandemic world may be necessary. The pandemic experience should be used as an opportunity to build a stronger community that is better prepared for catastrophe. This topic should be investigated from the operations management, work psychology, and ergonomics perspectives.

Table 8
The rough direct influence matrix (the integrated judgments of the experts).

	F1	F2	F3	F4	F5	F6	F7	F8
F1	[0, 0]	[1.682, 1.792]	[1.074, 2.052]	[1.458, 2.016]	[0.685, 1.468]	[1.009, 2.571]	[0.532, 1.614]	[0.776, 2.265]
F2	[0.607, 1.787]	[0, 0]	[1.518, 2.588]	[0.785, 1.886]	[0.7, 1.613]	[1.278, 2.266]	[0.697, 1.421]	[0.583, 1.756]
F3	[1.487, 2.308]	[0.781, 1.919]	[0, 0]	[0.961, 2.35]	[0.938, 1.643]	[0.68, 2.104]	[0.92, 2.521]	[1.154, 2.029]
F4	[1.372, 2.244]	[0.807, 1.457]	[1.268, 2.359]	[0, 0]	[0.879, 2.185]	[0.86, 2.106]	[1.033, 2.353]	[1.343, 2.281]
F5	[0.568, 1.585]	[0.684, 2.344]	[0.689, 1.733]	[1.357, 2.271]	[0, 0]	[0.77, 2.429]	[1.909, 2.659]	[0.835, 2.386]
F6	[0.976, 2.304]	[1.067, 2.385]	[1.416, 2.088]	[1.084, 2.207]	[1.411, 2.532]	[0, 0]	[1.498, 2.459]	[1.337, 2.618]
F7	[0.997, 2.344]	[1.632, 2.547]	[0.845, 2.255]	[0.647, 1.959]	[1.855, 3.139]	[0.915, 2.264]	[0, 0]	[0.959, 2.218]
F8	[0.878, 1.934]	[0.576, 1.683]	[1.495, 2.66]	[0.679, 1.93]	[1.291, 2.262]	[1.261, 2.76]	[1.503, 2.359]	[0, 0]

Table 9
The results of the Rough-Z-DEMATEL analysis.

	Rough R	Rough C	R	C	R+C	R−C	Weight	Rank
F1	[0.786, 10.679]	[0.758, 11.185]	5.733	5.971	11.704	−0.239	0.118	7
F2	[0.683, 10.321]	[0.792, 10.926]	5.502	5.859	11.362	−0.357	0.114	8
F3	[0.759, 11.425]	[0.898, 11.982]	6.092	6.440	12.532	−0.348	0.126	4
F4	[0.827, 11.536]	[0.764, 11.248]	6.181	6.006	12.188	0.175	0.123	6
F5	[0.753, 11.834]	[0.850, 11.441]	6.294	6.145	12.439	0.148	0.125	5
F6	[0.953, 12.577]	[0.742, 12.501]	6.765	6.622	13.387	0.143	0.135	1
F7	[0.849, 12.642]	[0.882, 11.810]	6.745	6.346	13.091	0.399	0.132	2
F8	[0.843, 11.974]	[0.767, 11.895]	6.409	6.331	12.739	0.078	0.128	3

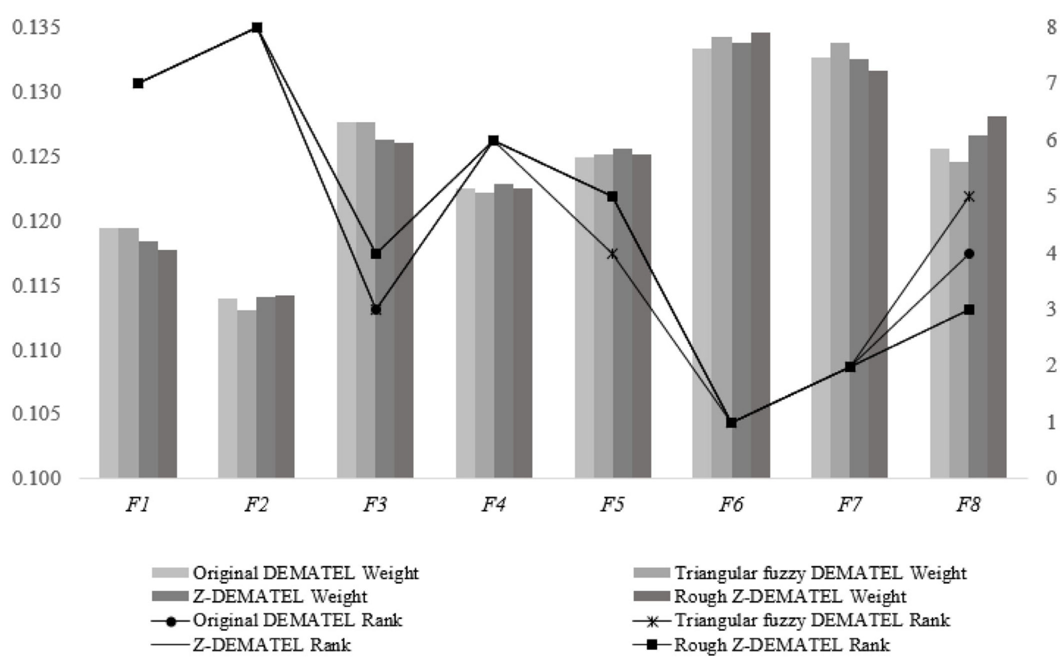

Fig. 3. Results analysis of the methods.

Table 10
Criteria weights and rankings obtained by the DEMATEL methods.

	Original DEMATEL		Triangular fuzzy DEMATEL		Z-DEMATEL		Rough Z-DEMATEL	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
F1	0.119	7	0.119	7	0.118	7	0.118	7
F2	0.114	8	0.113	8	0.114	8	0.114	8
F3	0.128	3	0.128	3	0.126	4	0.126	4
F4	0.122	6	0.122	6	0.123	6	0.123	6
F5	0.125	5	0.125	4	0.126	5	0.125	5
F6	0.133	1	0.134	1	0.134	1	0.135	1
F7	0.133	2	0.134	2	0.133	2	0.132	2
F8	0.126	4	0.125	5	0.127	3	0.128	3

6.2. Academic implications

This study is the first to explore the influential relationship of social innovation factors during the COVID-19 pandemic; it can act as a stepping stone for researchers and academicians to further explore other social factors under different scenarios. This study also acts as reference for comparing social innovation factors during and after the pandemic world, which helps the researchers to understand whether there is a shift in the importance of social innovation factors. The results will also help

Table 11
Comparison of the DEMATEL methods.

	Original DEMATEL	Triangular fuzzy DEMATEL	Z-DEMATEL	Rough Z-DEMATEL
Interaction relationship identification	✓	✓	✓	✓
Information uncertainty assessment		✓	✓	✓
Expert confidence measure			✓	✓
Multiple expert judgment integration				✓
Potential Information Coverage	Low	Medium	High	Very high

the policymakers and decision-makers in formulating policies for improving social innovation during disturbance like a pandemic. This study applied Rough-Z-DEMATEL to explore the influential relationship of social innovation factors. This technique is relatively new and taking a cue from this study, academicians and researchers can explore other similar application areas.

7. Conclusions and future work

This study developed a decision analysis framework for investigating social innovation taking into consideration the COVID-19 pandemic situation, to analyze the interdependencies among the related factors in the manufacturing context of a developing country. Twelve social innovation factors were initially identified through a comprehensive review of the literature. After the screening by a group of seven industry experts, eight social innovation factors, including traditional and COVID-19-related considerations were considered for further evaluation. The Rough-Z-DEMATEL model was developed for exploring the interrelationships among social innovation factors within a novel group decision-making scheme. Notably, introducing the social innovation factors during the COVID-19 pandemic and developing the Rough-Z-DEMATEL technique for investigating the mutual influence among social innovation factors are the major academic contributions of this article. The practical contribution of this study comes from the insights provided into the understanding of the social dimension of sustainable innovation taking into account the COVID-19 pandemic situation. The outcomes of this study help managers make well-informed decisions.

There are certain limitations to this study, which can offer directions for further development in the field. The first limitation of this work is that few experts from manufacturing companies of one emerging economy have participated. Future works can consider other sectors and countries or regions considering comparing the findings with those of this manuscript. The second limitation of this work is that the decision support framework considers a limited number of factors. Potential future works could employ industry-specific factors and sub-factors for more accurate outcomes. Besides, this paper investigated only the social aspect of sustainable innovation during the COVID-19 disaster. The third suggestion for future works comes from extending our investigations to account for environmental and economic aspects of sustainable innovation under COVID-19 circumstances and exploring the interrelationships and possible interactions between them. For this purpose, other MCDM tools, like Interpretive Structural Modeling (ISM) can be extended by employing fuzzy or rough numbers to handle information ambiguity and uncertainty. In so doing, the results could be compared with Rough-Z-DEMATEL to provide new insights. As the next suggestion for future research, the social innovation factors introduced in this study can inspire future studies on supply chains sustainability in times of major disasters. From a methodological perspective, future studies can integrate the stratified MCDM methods with DEMATEL or ISM to investigate the interrelationship among innovation factors considering uncertain situations and events that may happen in the future. Finally, social sustainability innovation research in developing countries is still in its early stages and requires more attention, especially in the era of the COVID-19 pandemic; this work can be considered a foundation for deeper studies on this research topic.

CRediT authorship contribution statement

Hadi Badri Ahmadi: Conceptualization, Writing – original draft. **Huai-Wei Lo:** Formal analysis, Methodology. **Pourya Pourhejazy:** Writing – original draft, Writing – review & editing. **Himanshu Gupta:** Supervision, Writing Discussion Section. **James J.H. Liou:** Supervision, Writing – review & editing.

Declaration of competing interest

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

References

[1] B.S. Silvestre, D.M. Ţîrcă, Innovations for sustainable development: Moving toward a sustainable future, J. Cleaner Prod. 208 (2019) 325–332.
[2] S. Kusi-Sarpong, H. Gupta, J. Sarkis, A supply chain sustainability innovation framework and evaluation methodology, Int. J. Prod. Res. 57 (7) (2019) 1990–2008.
[3] B. Sarkar, M. Sarkar, B. Ganguly, L.E. Cárdenas-Barrón, Combined effects of carbon emission and production quality improvement for fixed lifetime products in a sustainable supply chain management, Int. J. Prod. Econ. 231 (2020) 107867.
[4] T.D. Bui, F.M. Tsai, M.L. Tseng, R.R. Tan, K.D.S. Yu, M.K. Lim, Sustainable supply chain management towards disruption and organizational ambidexterity: a data driven analysis, Sustain. Prod. Consum. 26 (2020) 373–410.
[5] H. Gupta, M.K. Barua, A grey DEMATEL-based approach for modeling enablers of green innovation in manufacturing organizations, Environ. Sci. Pollut. Res. 25 (10) (2018) 9556–9578.
[6] J. Howaldt, R. Kopp, Shaping social innovation by social research, in: Challenge Social Innovation, Springer, Berlin, Heidelberg, 2012, pp. 43–55.
[7] J. Sarkis, M.J. Cohen, P. Dewick, P. Schröder, A brave new world: lessons from the COVID-19 pandemic for transitioning to sustainable supply and production, Resour. Conserv. Recy. 159 (2020) 104894.
[8] L.O. Gostin, L.F. Wiley, Governmental public health powers during the COVID-19 pandemic: stay-at-home orders, business closures, and travel restrictions, JAMA 323 (21) (2020) 2137–2138.
[9] M. Hakovirta, N. Denuwara, How COVID-19 redefines the concept of sustainability, Sustainability 12 (9) (2020) 3727.
[10] A. Kumar, S. Luthra, S.K. Mangla, Y. Kazançoğlu, COVID-19 impact on sustainable production and operations management, Sustain. Oper. Comput. 1 (2020) 1–7.
[11] H.B. Ahmadi, H.W. Lo, H. Gupta, S. Kusi-Sarpong, J.J. Liou, An integrated model for selecting suppliers on the basis of sustainability innovation, J. Cleaner Prod. 277 (2020) 123261.
[12] R. Kemp, Technology and environmental policy—Innovation effects of past policies and suggestions for improvement, Innov. Environ. 1 (2000) 35–61.
[13] Y. Tian, L. Liu, X. Mi, B. Kang, ZSLF: A new soft likelihood function based on Z-numbers and its application in expert decision system, IEEE Trans. Fuzzy Syst. (2020).
[14] R. Chutia, Ranking of Z-numbers based on value and ambiguity at levels of decision making, Int. J. Intell. Syst. 36 (1) (2021) 313–331.
[15] M. Yazdani, D. Pamucar, P. Chatterjee, S. Chakraborty, Development of a decision support framework for sustainable freight transport system evaluation using rough numbers, Int. J. Prod. Res. 58 (14) (2020) 4325–4351.

[16] H.B. Ahmadi, S. Kusi-Sarpong, J. Rezaei, Assessing the social sustainability of supply chains using Best Worst Method, Resour. Conserv. Recy. 126 (2017) 99–106.
[17] J. Sarkis, Q. Zhu, Environmental sustainability and production: taking the road less travelled, Int. J. Prod. Res. 56 (1–2) (2018) 743–759.
[18] P. Ahi, C. Searcy, A comparative literature analysis of definitions for green and sustainable supply chain management, J. Cleaner Prod. 52 (2013) 329–341.
[19] J.R.C. Vargas, C.E.M. Mantilla, A.B.L. de Sousa Jabbour, Enablers of sustainable supply chain management and its effect on competitive advantage in the Colombian context, Resour. Conserv. Recy. 139 (2018) 237–250.
[20] C. Yu, Y. Shao, K. Wang, L. Zhang, A group decision making sustainable supplier selection approach using extended TOPSIS under interval-valued Pythagorean fuzzy environment, Expert Syst. Appl. 121 (2019) 1–17.
[21] G.M. Silva, P.J. Gomes, J. Sarkis, The role of innovation in the implementation of green supply chain management practices, Bus. Strategy Environ. 28 (5) (2019) 819–832.
[22] M. Beise, K. Rennings, Lead markets and regulation: a framework for analyzing the international diffusion of environmental innovations, Ecol. Econom. 52 (1) (2005) 5–17.
[23] S. Aguado, R. Alvarez, R. Domingo, Model of efficient and sustainable improvements in a lean production system through processes of environmental innovation, J. Cleaner Prod. 47 (2013) 141–148.
[24] L. Albareda, A. Hajikhani, Innovation for sustainability: Literature review and bibliometric analysis, in: Innovation for Sustainability, Springer, 2019, pp. 35–57.
[25] A. Tariq, Y.F. Badir, W. Tariq, U.S. Bhutta, Drivers and consequences of green product and process innovation: A systematic review, conceptual framework, and future outlook, Technol. Soc. 51 (2017) 8–23.
[26] D. Yin, X. Ming, X. Zhang, Sustainable and Smart Product Innovation Ecosystem: An integrative status review and future perspectives, J. Cleaner Prod. 274 (2020) 123005.
[27] K.R. Nielsen, Policymakers' views on sustainable end-user innovation: Implications for sustainable innovation, J. Cleaner Prod. 254 (2020) 120030.
[28] C. Veldhuizen, Conceptualising the foundations of sustainability focused innovation policy: From constructivism to holism, Technol. Forecast. Soc. Change 162 (2020) 120374.
[29] H. Gupta, S. Kusi-Sarpong, J. Rezaei, Barriers and overcoming strategies to supply chain sustainability innovation, Resour. Conserv. Recy. 161 (2020) 104819.
[30] E. Pol, S. Ville, Social innovation: Buzz word or enduring term? J. Socio-Econ. 38 (6) (2009) 878–885.
[31] S.V. Ramani, S. SadreGhazi, S. Gupta, Catalysing innovation for social impact: The role of social enterprises in the Indian sanitation sector, Technol. Forecast. Soc. Change 121 (2017) 216–227.
[32] M. McKelvey, O. Zaring, Co-delivery of social innovations: exploring the university's role in academic engagement with society, Ind. Innov. 25 (6) (2018) 594–611.
[33] B.S. Saji, P. Ellingstad, Social innovation model for business performance and innovation, Int. J. Prod. Perform. Manage. 65 (2) (2016) 256–274.
[34] S. Ozdemir, D. Kandemir, T.Y. Eng, The role of horizontal and vertical new product alliances in responsive and proactive market orientations and performance of industrial manufacturing firms, Ind. Mark. Manag. 64 (2017) 25–35.
[35] V.H. Remko, Research opportunities for a more resilient post-COVID-19 supply chain–closing the gap between research findings and industry practice, Int. J. Oper. Prod. Manage. (2020).
[36] K. Govindan, H. Mina, B. Alavi, A decision support system for demand management in healthcare supply chains considering the pandemic outbreaks: A case study of coronavirus disease 2019 (COVID-19), Transp. Res. E 138 (2020) 101967.
[37] A. Majumdar, M. Shaw, S.K. Sinha, COVID-19 debunks the myth of socially sustainable supply chain: A case of the clothing industry in South Asian countries, Sustain. Prod. Consum. 24 (2020) 150–155.
[38] A. Sharma, A. Adhikary, S.B. Borah, Covid-19's impact on supply chain decisions: Strategic insights for NASDAQ 100 firms using twitter data, J. Bus. Res. 117 (2020) 443–449.
[39] E. Koberg, A. Longoni, A systematic review of sustainable supply chain management in global supply chains, J. Cleaner Prod. 207 (2019) 1084–1098.
[40] N. Jain, A.R. Singh, Sustainable supplier selection under must-be criteria through Fuzzy inference system, J. Cleaner Prod. 248 (2020) 119275.
[41] M. Abdel-Basset, R. Mohamed, A novel plithogenic TOPSIS-CRITIC model for sustainable supply chain risk management, J. Cleaner Prod. 247 (2020) 119586.
[42] Z. Zhu, F. Chu, A. Dolgui, C. Chu, W. Zhou, S. Piramuthu, Recent advances and opportunities in sustainable food supply chain: a model-oriented review, Int. J. Prod. Res. 56 (17) (2018) 5700–5722.
[43] Z. Chen, X. Ming, T. Zhou, Y. Chang, Sustainable supplier selection for smart supply chain considering internal and external uncertainty: An integrated rough-fuzzy approach, Appl. Soft Comput. 87 (2020) 106004.
[44] K. Govindan, K. Muduli, K. Devika, A. Barve, Investigation of the influential strength of factors on adoption of green supply chain management practices: An Indian mining scenario, Resour. Conserv. Recy. 107 (2016) 185–194.
[45] M. Schäfer, M.D. de Figueiredo, S. Iran, M. Jaeger-Erben, M.E. Silva, J.C. Lazaro, M. Meißner, Imitation, adaptation, or local emergency?–A cross-country comparison of social innovations for sustainable consumption in Brazil, Germany, and Iran, J. Cleaner Prod. (2020) 124740.
[46] V. Cattivelli, V. Rusciano, Social innovation and food provisioning during COVID-19: The case of urban-rural initiatives in the province of Naples, Sustainability 12 (11) (2020) 4444.
[47] C.H.K. Chui, A. Ko, Converging humanitarian technology and social work in a public health crisis: a social innovation response to COVID-19 in Hong Kong, Asia Pac. J. Soc. Work Dev. 31 (1–2) (2021) 59–66.
[48] R. Arocena, J. Sutz, Universities and social innovation for global sustainable development as seen from the south, Technol. Forecast. Soc. Change 162 (2020) 120399.
[49] L. Rodrigo, M. Palacios, What antecedent attitudes motivate actors to commit to the ecosystem of digital social innovation? Technol. Forecast. Soc. Change 162 (2020) 120394.
[50] M.M. Babu, B.L. Dey, M. Rahman, S.K. Roy, S.F.S. Alwi, M.M. Kamal, Value co-creation through social innovation: A study of sustainable strategic alliance in telecommunication and financial services sectors in Bangladesh, Ind. Mark. Manag. 89 (2020) 13–27.
[51] A. Ludvig, S. Sarkki, G. Weiss, I. Živojinović, Policy impacts on social innovation in forestry and back: Institutional change as a driver and outcome, Forest Policy Econ. 122 (2020) 102335.
[52] F.S. Farzad, Y. Salamzadeh, A.B. Amran, A. Hafezalkotob, Social Innovation: Towards a better life after COVID-19 crisis: What to concentrate on, J. Entrepreneurship. Bus. Econ. 8 (1) (2020) 89–120.
[53] M.H. Li, Proactive strategies, social innovation, and community engagement in relation to COVID-19 in taiwan, in: Coronavirus (COVID-19) Outbreaks, Environment and Human Behaviour: International Case Studies, 2021, p. 49.
[54] D. Ivanov, Viable supply chain model: integrating agility, resilience and sustainability perspectives—lessons from and thinking beyond the COVID-19 pandemic, Ann. Oper. Res. (2020) 1–21.
[55] M.M. Queiroz, D. Ivanov, A. Dolgui, S.F. Wamba, Impacts of epidemic outbreaks on supply chains: mapping a research agenda amid the COVID-19 pandemic through a structured literature review, Ann. Oper. Res. (2020) 1–38.
[56] H.W. Lo, J.J. Liou, C.N. Huang, Y.C. Chuang, A novel failure mode and effect analysis model for machine tool risk analysis, Reliab. Eng. Syst. Saf. 183 (2019) 173–183.
[57] L.A. Zadeh, A note on Z-numbers, Inform. Sci. 181 (14) (2011) 2923–2932.
[58] L.Y. Zhai, L.P. Khoo, Z.W. Zhong, A rough set enhanced fuzzy approach to quality function deployment, Int. J. Adv. Manuf. Technol. 37 (5–6) (2008) 613–624.
[59] T.W. Chang, H.W. Lo, K.Y. Chen, J.J. Liou, A novel FMEA model based on rough BWM and rough TOPSIS-AL for risk assessment, Mathematics 7 (10) (2019) 874.
[60] M. Gul, Emergency department ergonomic design evaluation: A case study using fuzzy DEMATEL-focused two-stage methodology, Health Policy Technol. 8 (4) (2019) 365–376.
[61] W.C.J. Hsu, J.J. Liou, H.W. Lo, A group decision-making approach for exploring trends in the development of the healthcare industry in Taiwan, Decis. Support Syst. 141 (2021) 113447.
[62] P. Ghadimi, A. Dargi, C. Heavey, Making sustainable sourcing decisions: practical evidence from the automotive industry, Int. J. Logist. Res. Appl. 20 (4) (2017) 297–321.
[63] J. Rezaei, R. Ortt, V. Scholten, Measuring entrepreneurship: Expert-based vs. data-based methodologies, Expert Syst. Appl. 39 (4) (2012) 4063–4074.
[64] M.A. Moktadir, H.B. Ahmadi, R. Sultana, J.J. Liou, J. Rezaei, Circular economy practices in the leather industry: A practical step towards sustainable development, J. Cleaner Prod. 251 (2020) 119737.
[65] H.B. Ahmadi, H.W. Lo, H. Gupta, S. Kusi-Sarpong, J.J. Liou, Analyzing interrelationships among environmental sustainability innovation factors, Clean Technol. Environ. Policy (2021) 1–17.
[66] P. Pourhejazy, A. Ashby, Reshoring decisions for adjusting supply chains in a changing world: A case study from the apparel industry, Int. J. Environ. Res. Public Health 18 (9) (2021) 4873.