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An integrated information fusion and grey multi-criteria decision-making framework for sustainable supplier selection

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ABSTRACT
The recent changes in global business markets have forced supply chains to include sustainability and considerable uncertainty in their decision-making processes. In this study, we propose an integrated information fusion and grey multi-criteria decision-making (MCDM) framework for solving sustainable supplier selection problems with imprecise information. We identify a series of criteria in the literature based on the economic, social, and environmental aspects of sustainability and obtain the relative importance of these criteria from experts' opinions. We then propose a best-worst method (BWM) integrated with grey theory to calculate the weights of criteria. These weights are used to evaluate a set of suppliers based on three sustainability aspects. A hybrid method composed of weighted aggregated sum product assessment (WASPAS), the technique for order of preference by similarity to ideal solution (TOPSIS), and grey theory are proposed for ranking the suppliers. We aggregate the grey MCDM results with the concept of information fusion to find an integrated score for each supplier. The final ranking is obtained by incorporating expert opinions with the integrated scores. We also present a case study to demonstrate the applicability of the proposed framework. A sensitivity analysis is performed to test the reliability and robustness of the results.

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Sustainable supplier selection; grey theory; best-worst method; weighted aggregated sum product assessment (WASPAS); TOPSIS; information fusion

1. Introduction

Supplier selection is considered one of the most crucial decisions in a supply chain affecting different tasks. (Govindan et al., 2013; Sarkis & Dhavale, 2015; Tavana et al., 2017). Evaluating and selecting suitable suppliers is an arduous task since it usually includes complexity and uncertainty (Fallahpour et al., 2017). In recent decades, because of globalisation and increased knowledge of communities in terms of environmental problems and social responsibilities of business entities, this intricate problem has become more challenging. These changes emerged as a new concept known as sustainability (Luthra et al., 2017). As a result, supply chains have changed their focus from solely economic criteria to include environmental and social dimensions (Sancha et al., 2015). However, sustainability can affect various aspects of a supply chain such as product design, material purchasing, manufacturing processes, and quality of goods and performance of organisations (Govindan et al., 2013; Tavana et al., 2017). Hence, the importance of supplier selection has become more and more accentuated, considering the new sustainability element in supply chain activities.

Selecting the suppliers with the highest potential can bring about several benefits to a company. Not only can a company satisfy its needs, but also it can reduce its expenses very effectively. Suitable suppliers can provide enterprises with strong manufacturing performance as well as maximum monetary benefits (Pitchipoo et al., 2013). In the sustainable supplier selection problem, one should consider the interdependencies among sustainability criteria relevant to supplier selection and determine supplier performance with respect to these criteria (Orji & Wei, 2014).

The supplier selection process consists of several steps. This process usually starts by identifying a series of criteria addressing the specific needs of customers and organisations in a supply chain. Then, an evaluation step should be conducted using a suitable approach to rank the available suppliers based on the selected criteria. Both quan-

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titative and qualitative measures must be considered in the evaluation process (Govindan et al., 2013; Zimmer et al., 2016). The sustainable supplier selection problems are MCDM problems requiring consideration of multiple objectives (Sarkis & Dhavale, 2015).

However, in real cases, a degree of uncertainty in the decision process is inevitable. This imprecise information mainly stems from a subjective evaluation of specific criteria by decision-makers (Govindan et al., 2013). The effects of this uncertainty can sometimes affect the whole network of a supply chain. Not only the related risk to the aforementioned uncertainty can diminish the performance of a supply chain, but also it can jeopardise the supply chain altogether. The famous example of Nokia and Ericsson can mirror the severity of these effects (Scheibe & Blackhurst, 2018). Moreover, major unexpected natural or human-made disasters such as earthquakes, fires, floods, hurricanes, or economic crises can interfere with the natural processes of a supply chain. (Heckmann et al., 2015). For instance, the recent disruptions in the electronics supply chains due to the Japan earthquake and Thailand flooding in 2011, resulted in huge losses of many Japanese companies (Sawik, 2014). Typically, this vague information can be translated to calculable information using fuzzy or grey theories. Therefore, it seems promising to investigate the sustainable supplier selection problem in real-life problems by integrating MCDM methods with theories, which can handle the ambiguity of human judgments.

Information fusion is a method for integrating data acquired from multiple sources into reliable and accurate information to achieve actionable inferences. Although this method has been widely used in communication problems, it can be utilised to produce a unified ranking from different MCDM methods (Chen & Ben-Arieh, 2006). Several MCDM methods have been proposed in the literature. Due to the intrinsic differences in these methods, they tackle the same problem from different angles and often produce dissimilar results (Peng et al., 2011). A key challenge in MCDM is different methods with the same input often produce incompatible rankings. Therefore, finding an overall aggregated ranking of alternatives is not a straightforward task (Mohammadi & Rezaei, 2020). In such cases, information fusion could be used to synthesise the outputs from different MCDM methods (Deng et al., 2011).

The remainder of the paper is organised as follows: In Section 2, a structured literature review of sustainable supplier selection is presented. The different aspects of the proposed integrated approach are explained in Section 3. A real-world case study is presented in Section 4 to demonstrate the applicability and exhibit the efficacy of the proposed supplier selection method. A sensitivity analysis to monitor the robustness of the method is also conducted in this section. Finally, the conclusion and possible paths for future research are included in Section 5.

2. Literature review

Researchers have approached the sustainable supplier selection problem with different methods. Hence, the literature review is divided into four separate sections. At first, studies investigating sustainable supplier selection using MCDM methods are presented. In the second section, the studies that consider the integrated approaches to deal with the ambiguity of information are presented. Then, the studies that implement more complicated methods in sustainable supplier selection are mentioned. Finally, the articles that use the best-worst method (BWM) for calculating weights phase in sustainable supplier selection problem are mentioned.

2.1. MCDM approaches

Since researchers usually deal with a multi-criteria environment in the supplier selection problem, MCDM methods are commonly used in the solution procedure. Different methods such as (analytic hierarchy process) AHP, analytic network process (ANP), and Decision-making Trial and Evaluation Laboratory (DEMATEL) can be found in the literature. AHP was used for ranking the available suppliers as well as calculating the weights of criteria in different papers such as Kannan et al. (2008) and Sivakumar et al. (2015). Likewise, Hsu and Hu (2009) presented an ANP approach to incorporate the issue of hazardous substance management (HSM) into supplier selection. DEMATEL was implemented in the work of Hsu et al. (2013) to recognise the influential criteria of carbon management in the green supply chain for improving the overall performance of suppliers in terms of carbon management.

2.2. Integrated approaches

Researchers have recently opted to integrated approaches so that they can combine the advantages of traditional MCDM methods with fuzzy and grey theories in order to better handle human knowledge.

2.2.1. Fuzzy theory

The most widely used approaches are fuzzy-AHP, fuzzy ANP, fuzzy- Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and fuzzy inference system (FIS). Lee et al. (2009) implemented a fuzzy extended analytic hierarchy process to consider the vagueness of experts' opinions in the sustainable supplier selection problem (SSSP). Shaw et al. (2012) presented an integrated approach based on fuzzy-AHP and fuzzy multi-objective linear programming for supplier selection in the supply chain addressing the carbon emission issue. Fuzzy-ANP was also utilised by Büyüközkan and Çifçi (2011) to investigate the problem of identifying an effective model based on sustainability principles for supplier selection operations in supply chains. Moreover, integrating the fuzzy set theory and TOPSIS method is an effective way to study the SSSP. This integrated approach can be found in recent articles such as Govindan et al. (2013), Shen et al. (2013), Kannan et al. (2014), and Orji and Wei (2014). The fuzzy inference system (FIS) is another approach for addressing the SSSP problem considering the expert's knowledge. This method was utilised in Amindoust et al. (2012) and Ghadimi and Heavey (2014).

2.2.2. Grey theory

Some researchers prefer using grey theory due to its less computational complexity compared to fuzzy theory. Bai and Sarkis (2010) presented a novel approach utilising a grey system and rough set theory. They asserted that their contribution included an introduction of additional levels of analysis and application of this methodology, the explicit consideration of sustainability attributes, and insights into the technique with some sensitivity analysis. Dou et al. (2014) developed a grey ANP model to identify green supplier development programmes, improving suppliers' performance. They used a real-world example to demonstrate the effectiveness of the model. Hashemi et al. (2015) used economic and environmental criteria to propose a comprehensive green supplier selection model. ANP was used to deal with the interdependencies among the criteria. The traditional grey relational analysis (GRA) was also modified to address the uncertainties inherent in supplier selection decisions. They used a case study in the automotive industry. Su et al. (2016) proposed a hierarchical grey DEMATEL to identify and analyse criteria and alternatives. They used the grey theory for incomplete information. They applied the proposed method to identify aspects of and criteria for supplier prioritisation. Song et al. (2017) considered the interrelationships among economic, environmental, and social evaluation criteria in the supplier selection. They developed a novel integrated methodology. Their proposed method integrated pairwise comparison, DEMATEL, and the rough number's advantages. A case study in a solar air-conditioner manufacturer was provided to show the feasibility and effectiveness of the proposed methodology. Haeri and Rezaei (2019) proposed a comprehensive grey-based green supplier selection model to includes both economic and environmental criteria. They used a novel weight assignment method by combining the best-worst method and fuzzy grey cognitive maps to capture the interdependencies among the criteria. They evaluated the applicability and effectiveness of the proposed method with a real-world case study. Hatami-Marbini et al. (2020) developed a unified structure for supplier selection under uncertainty. They implemented a grey-based multi-attribute efficiency analysis model by combining principal component analysis and data envelopment analysis (PCA-DEA) for supplier selection. They used a real-world case study in the agri-food industry to demonstrate the advantages and applicability of their framework.

Table 1 presents a comparison between the model proposed in this study and other grey-based models in the literature.

2.3. Other approaches

Papers in this category used other unique integrated methods to deal with the complexity of the SSSP. Data envelopment analysis (DEA) is one of the most popular methods in the literature. Bai and Sarkis (2014), Azadi et al. (2015), and Mahdiloo et al. (2015) are the most recent articles in which this procedure is used to evaluate and rank the suppliers in a supply chain. Other researchers approached the SSSP with more innovative methods. Kannan et al. (2015) proposed a multi-criteria decision-making (MCDM) approach called Fuzzy Axiomatic Design (FAD) to select the best green supplier for a Singapore-based plastic manufacturing company. Sarkis and Dhavale (2015) developed a novel methodological approach based on a Bayesian framework and Monte Carlo Markov Chain (MCMC) simulation to rank and select suppliers using specific selection objectives. Orji and Wei (2015) developed a novel modelling approach for integrating information on supplier behaviour in a fuzzy environment. Akman (2015) used a two-step clustering by using a c-means clustering method to categorise the suppliers in different segments based on specific criteria. Trapp and Sarkis (2016) developed an optimisation model using an algorithmic approach that simultaneously addressed supplier selection, supplier development, and sustainability considerations. Tavana et al. (2017) proposed a novel integrated multi-criteria decision-making approach to sustainable supplier selection problems. For ranking the suppliers, they used a multi-objective optimisation procedure based on ratio analysis and weighted aggregated sum product assessment (WASPAS). Fallahpour et al.

Table 1. Comprehensive review of the grey MCDM approaches for supplier selection.

Author(s)	Approach	Sustainable supplier selection	Economic	Social	Environmental	Case Study	Information Fusion	Scope
Bai and Sarkis (2010)	Grey theory, rough set theory	✓	✓	✓	✓	–	–	–
Baskaran et al. (2012)	Grey theory	✓	✓	✓	✓	✓	–	Textile and clothing industry
Fu et al. (2012)	Grey DEMATEL	–	–	–	✓	✓	–	Telecommunications equipment provider in China
Dou et al. (2014)	Grey ANP	–	✓	–	✓	✓	–	Irrigation equipment industry
Hashemi et al. (2015)	Modified GRA and ANP	–	✓	–	✓	✓	–	Automotive industry
Memon et al. (2015)	Grey theory, Uncertainty theory	✓	✓	✓	✓	–	–	–
Rajesh and Ravi (2015)	GRA	–	✓	–	✓	✓	–	Electronic supply chain
Su et al. (2016)	Hierarchical grey decision-making	✓	✓	✓	✓	✓	–	Taiwanese electronic manufacturing
Ahmadi et al. (2017)	AHP and improved GRA	✓	✓	✓	✓	✓	–	Telecom industry
Song et al. (2017)	DEMATEL and rough set theory	✓	✓	✓	✓	✓	–	Solar air-conditioner manufacturer
Haeri and Rezaei (2019)	BWM and fuzzy grey cognitive maps	–	✓	–	✓	✓	–	–
Hatami-Marbini et al. (2020)	Grey PCA-DEA	–	✓	–	–	✓		Agri-food industry
Current study	Grey TOPSIS, Grey WASPAS, Grey BWM	✓	✓	✓	✓	✓	✓	Electrified pickup trucks

(2017) proposed a hybrid model to identify the most sustainable suppliers with respect to the determined attributes using an Iranian textile manufacturing company as a case study. Sinha and Anand (2018) presented a framework for supplier selection from a sustainability perspective. They proposed a sustainable supplier selection attributes graph and a sustainable supplier selection index to consider the interrelationships of criteria and appraising the suppliers, respectively. Zhou and Xu (2018) proposed a novel criteria system for evaluating sustainable suppliers from three aspects and six dimensions as well as an integrated evaluation model. A real case of a large supermarket was introduced and analysed to verify the applicability and effectiveness of the proposed method.

The BWM is a relatively novel MDCM technique for calculating weights of criteria in multi-criteria problems. This method has been used to solve a wide range of MCDM problems (see You et al., 2017 and Zolfani et al., 2019). Table 2 shows selected articles using this new method for supplier selection.

2.4. Research gaps

We have identified the following gaps in the literature in support of our proposed integrated framework:

(1) Several researchers have proposed various MCDM approaches with well-known shortfalls. For example, the AHP method can sometimes lead to inconsistencies between judgments and ranking criteria. Likewise, it cannot handle interconnections among different criteria. However, other approaches, such as DEA, are not also very effective in real SSSP problems. DEA does not deal with imprecise data since it assumes that all input and output are exactly known. Moreover, to overcome the limitations of conventional MCDM methods, researchers have focused on hybrid and integrated frameworks. The fuzzy set theory has been used to represent uncertainty and ambiguity in MCDM problems. However, fuzzy MCDM methods involve complicated computations depending on the type of fuzzy numbers used to represent uncertainty (i.e. triangular, trapezoidal, etc.). In addition, selecting suitable fuzzy numbers or fuzzy membership functions is somewhat contentious. We use grey theory to address these drawbacks. Furthermore, the computational time of our method is significantly lower than the analogous methods. The integration of grey theory with the BWM to determine the criteria weights is a significant contribution of the method proposed in this study.

(2) Many studies have proposed different MCDM methods for supplier evaluation and selection. However, most of these studies do not integrate the results obtained from different sources. We use information fusion to bridge this gap. We designed an information fusion algorithm to integrate the rankings and find the most suitable supplier. The proposed

Table 2. Articles using BWM in the supplier selection problem.

Author(s)	Approach	Purpose
Rezaei et al. (2016)	BWM	To propose an innovative three-phase supplier selection methodology including pre-selection, selection, and aggregation
Gupta and Barua (2017)	BMW	To develop a framework for supplier selection by large organisations
Lo et al. (2018)	BWM	To propose a novel model to solve problems in green supplier selection and order allocation
Cheraghalipour and Farsad (2018)	BMW	To develop a decision-making tool in a multi-period, multi-item, and multi-supplier environment considering quantity discounts and disruption risks
Liu et al. (2018)	Fuzzy BWM	To propose a novel two-stage fuzzy integrated MCDM method to select suitable suppliers
Bai et al. (2019)	Grey-BWM and TODIM	To propose a social sustainability attribute decision framework to evaluate and select socially sustainable suppliers
Liu et al. (2019)	BWM and alternative queuing method (AQM)	to capture the uncertainty and vagueness of decision makers' judgements with the aid of interval-valued intuitionistic uncertain linguistic sets
Haeri and Rezaei (2019)	BWM and fuzzy grey cognitive maps	To propose a comprehensive grey-based green supplier selection model to include both economic and environmental criteria

method ensures the various methods used in the proposed framework all have an applicable impact on the results. The proposed framework for information fusion considers expert opinions and the outputs of the MCDM methods to find the final aggregated ranking, which is another contribution of this study.

3. Methodology

In this section, the proposed methods are explained thoroughly. At first, a grey BMW method is implemented to obtain the weights of the selected criteria. Then, two proposed methods, grey WASPAS and grey TOPSIS, are presented, both of which are used to rank the pool of available suppliers. An information fusion method is used to integrate the results obtained from different MCDM techniques used throughout the process.

3.1. Grey BWM

The BWM is a recently developed MCDM technique introduce by Rezaei (2015) to eliminate the natural drawbacks of other similar methods for calculating weights of criteria. This method is solely based on pairwise comparisons among all criteria and the best and the worst ones. However, it has some advantages over other methods such as AHP. Not only does it need fewer pairwise comparisons than AHP, but also, the acquired results are more robust (Rezaei, 2015). In order to assess the consistency of the results, an inconsistency rate (IR) is calculated. Bai et al. (2019) proposed a similar grey-based BWM; however, the method proposed in this study defines an IR rate based on the grey intervals to assess the consistency of the results. This will affect two aspects of this method. Firstly, the proposed linear method by Rezaei (2016) will change, as shown in Eq. (1) to (6).

$$\begin{aligned}&\text{Min } \delta\\&s.t.\end{aligned} \tag{1}$$

$$|[\underline{w}_B, \overline{w}_B] - [\underline{a}_{Bj}, \overline{a}_{Bj}][\underline{w}_j, \overline{w}_j]| \leq [\delta, \delta], \quad \forall j \tag{2}$$

$$|[\underline{w}_j, \overline{w}_j] - [\underline{a}_{jW}, \overline{a}_{jW}][\underline{w}_w, \overline{w}_w]| \leq [\delta, \delta], \quad \forall j \tag{3}$$

$$\underline{w}_j \geq 0, \overline{w}_j \geq 0, \quad \forall j \tag{4}$$

$$\underline{w}_j \leq \overline{w}_j, \quad \forall j \tag{5}$$

$$\sum_{j=1}^{n} \frac{\underline{w}_j + \overline{w}_j}{2} = 1, \quad \forall j = 1, 2, \ldots, n \tag{6}$$

Secondly, the procedure through which IR numbers are calculated varies slightly. We used the proposed method in Guo and Zhao (2017) for calculating these numbers. Readers are encouraged to read the cited paper to become more familiar with the procedure used for fuzzy numbers. Table 3 depicts the grey intervals, their linguistic equivalents in the pairwise comparisons, and IR numbers. The detailed steps of the procedure are provided in section 4.

Table 3. The intervals of grey BWM.

Interval	Linguistic	IR
[0,2]	Very Low	0.438
[2,4]	Low	1.628
[4,6]	Medium	3
[6,8]	High	4.469
[8,10]	Very High	6

3.2. Grey WASPAS

The WASPAS method is one of the most recently developed multi-criteria decision-making methods, which was introduced by Zavadskas et al. (2012). This method is a combination of the WSM (weighted sum model) and WPM (weighted product model). This method has more accuracy compared to the independent methods, though. It is like other approaches such as TOPSIS or Vlse Kriterijuska Optimizacija I Komoromisno Resenje (VIKOR) regarding the criterion-alternative matrix. It also needs the weights of the criteria for the ranking of alternatives. These weights can be calculated via the AHP or other methods such as Shannon Entropy, grey Entropy, or the BWM. Zavadskas et al. (2015) introduced the grey version of this method, including the following steps:

(a) Normalising the Decision Matrix: In this step, using the following equations, the decision matrix should be normalised. For normalising the positive criterion, Eq.(7), and for the negative criterion, Eq.(8) are implemented.

$$\otimes x_{ij} = \left[\frac{\underline{G}_{ij}}{G_j^{\mathrm{Max}}}, \frac{\bar{G}_{ij}}{G_j^{\mathrm{Max}}}\right]; \quad G_j^{\mathrm{Max}} = \mathrm{Max}\{\bar{G}_{ij}\} \quad (7)$$

$$\otimes x_{ij} = \left[\frac{G_j^{\min}}{\bar{G}_{ij}}, \frac{G_j^{\min}}{\underline{G}_{ij}}\right]; \quad G_j^{\min} = \min\{\underline{G}_{ij}\} \quad (8)$$

(b) Calculating the relative importance of alternatives based on the weighted sum method (WSM) for both upper and lower bounds of each alternative using Eqs. (9) and (10).

$$\bar{Q}_i^{(1)} = \sum_{j=1}^{n} \bar{x}_{ij}\bar{w}_j \quad (9)$$

$$\underline{Q}_i^{(1)} = \sum_{j=1}^{n} \underline{x}_{ij}\underline{w}_j \quad (10)$$

(c) Calculating the relative importance of alternatives based on the weighted product method (WPM) for both upper and lower bounds of each alternative using Eqs. (11) and (12).

$$\bar{Q}_i^{(2)} = \prod_{j=1}^{n} (\bar{x}_{ij})^{\bar{w}_j} \quad (11)$$

$$\underline{Q}_i^{(2)} = \prod_{j=1}^{n} (\underline{x}_{ij})^{\underline{w}_j} \quad (12)$$

(d) Calculating the common criterion: In this step with equal proportions of WSM and WPM, the importance for both upper and lower bounds of the alternatives is calculated by Eqs. (13) and (14).

$$\bar{Q}_i = 0.5\bar{Q}_i^{(1)} + 0.5\bar{Q}_i^{(2)} = 0.5\sum_{j=1}^{n} \bar{x}_{ij}\bar{w}_j + 0.5\prod_{j=1}^{n} (\bar{x}_{ij})^{\bar{w}_j} \quad (13)$$

$$\underline{Q}_i = 0.5\underline{Q}_i^{(1)} + 0.5\underline{Q}_i^{(2)} = 0.5\sum_{j=1}^{n} \underline{x}_{ij}\underline{w}_j + 0.5\prod_{j=1}^{n} (\underline{x}_{ij})^{\underline{w}_j} \quad (14)$$

Alternatives can be ranked based on Q_i. However, the precision and impact of the WASPAS method are that the relative importance of the i th alternative is calculated by computing lambda for upper and lower bounds using the following equations:

$$\bar{Q}_i = \bar{\lambda}\bar{Q}_i^{(1)} + (1-\bar{\lambda})\bar{Q}_i^{(2)} = \bar{\lambda}\sum_{j=1}^{n} \bar{x}_{ij}\bar{w}_j + (1-\bar{\lambda})\prod_{j=1}^{n} (\bar{x}_{ij})^{\bar{w}_j} \quad (15)$$

$$\underline{Q}_i = \underline{\lambda}\underline{Q}_i^{(1)} + (1-\underline{\lambda})\underline{Q}_i^{(2)} = \underline{\lambda}\sum_{j=1}^{n} \underline{x}_{ij}\underline{w}_j + (1-\underline{\lambda})\prod_{j=1}^{n} (\underline{x}_{ij})^{\underline{w}_j} \quad (16)$$

$$Q_i = 0.5\bar{Q}_i + 0.5\underline{Q}_i \quad (17)$$

The following equations are used to calculate the optimal lambda based on standard deviations:

$$\bar{\lambda} = \frac{\sigma^2(\bar{Q}_i^{(2)})}{\sigma^2(\bar{Q}_i^{(1)}) + \sigma^2(\bar{Q}_i^{(2)})} \qquad \underline{\lambda} = \frac{\sigma^2(\underline{Q}_i^{(2)})}{\sigma^2(\underline{Q}_i^{(1)}) + \sigma^2(\underline{Q}_i^{(2)})} \quad (18)$$

$$\sigma^2(\underline{Q}_i^{(1)}) = \sum_{j=1}^{n} \underline{w}_j^2\sigma^2(\underline{x}_{ij}) \quad \sigma^2(\bar{Q}_i^{(1)}) = \sum_{j=1}^{n} \bar{w}_j^2\sigma^2(\bar{x}_{ij}) \quad (19)$$

$$\sigma^2(\underline{Q}_i^{(2)}) = \sum_{j=1}^{n}\left(\frac{\prod_{j=1}^{n}(\underline{x}_{ij})^{\underline{w}_j}\underline{w}_j}{(\underline{x}_{ij})^{\underline{w}_j}(\underline{x}_{ij})^{(1-\underline{w}_j)}}\right) \qquad \sigma^2(\bar{Q}_i^{(2)}) = \sum_{j=1}^{n}\left(\frac{\prod_{j=1}^{n}(\bar{x}_{ij})^{\bar{w}_j}\bar{w}_j}{(\bar{x}_{ij})^{\bar{w}_j}(\bar{x}_{ij})^{(1-\bar{w}_j)}}\right) \quad (20)$$

$$\sigma^2(\underline{x}_{ij}) = (0.05\underline{x}_{ij})^2 \quad \sigma^2(\bar{x}_{ij}) = (0.05\bar{x}_{ij})^2 \quad (21)$$

(a) Ranking suppliers: in this step, the suppliers are ranked based on their score index Q_i considering the optimum lambda.

3.3. Grey TOPSIS

The grey TOPSIS is very similar to the conventional TOPSIS method, which is used to rank the alternatives (See Zolfani et al., 2012). However, this method is based on grey numbers. This method is composed of the following steps:

(a) Forming the decision matrix, identifying the positive and negative criteria, and calculating the weights of criteria by methods such as grey Entropy, grey AHP, grey BWM, or definite weights.

$$D = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1n} \\ G_{21} & G_{22} & \cdots & G_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ G_{m1} & G_{m2} & \cdots & G_{mn} \end{bmatrix} \tag{22}$$

(b) Normalising the decision matrix: In this step, the grey decision matrix must be normalised to convert all its numbers between zero and one. Normalisation is done using the following formulas. If the criterion has a positive aspect, Eq. (23) is used. If the criterion has a negative nature, Eq. (24) is used.

$$\otimes G^*{}_{ij} = \left[\frac{\underline{G}_{ij}}{G_j^{\mathrm{Max}}}, \frac{\bar{G}_{ij}}{G_j^{\mathrm{Max}}}\right]; \quad G_j^{\mathrm{Max}} = \mathrm{Max}\{\bar{G}_{ij}\} \tag{23}$$

$$\otimes G^*{}_{ij} = \left[\frac{G_j^{\min}}{\bar{G}_{ij}}, \frac{G_j^{\min}}{\underline{G}_{ij}}\right]; \quad G_j^{\min} = \min\{\underline{G}_{ij}\} \tag{24}$$

$$D^* = \begin{bmatrix} G^*_{11} & G^*_{12} & \cdots & G^*_{1n} \\ G^*_{21} & G^*_{22} & \cdots & G^*_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ G^*_{m1} & G^*_{m2} & \cdots & G^*_{mn} \end{bmatrix} \tag{25}$$

(c) Creating the weighted normal matrix: In this step, the grey values of weights are multiplied by the normal matrix.

$$D = \begin{bmatrix} V_{11} & V_{12} & \cdots & V_{1n} \\ V_{21} & V_{22} & \cdots & V_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ V_{m1} & V_{m2} & \cdots & V_{mn} \end{bmatrix} \tag{26}$$

$$V_{ij} = [\underline{G}^*_{ij} \times \underline{w}_j, \bar{G}^*_{ij} \times \bar{w}_j] \tag{27}$$

(d) Calculating the Ideal points: In this step, the maximum limit for upper and lowers bounds for each criterion should be determined.

$$A^{\max} = \{[\max \underline{V_{i1}}, \max \overline{V_{i1}}], [\max \underline{V_{i2}}, \max \overline{V_{i2}}], \ldots, [\max \underline{V_{in}}, \max \overline{V_{in}}]\} \tag{28}$$

(e) Calculating the grey possibility: In this step, the probability that a grey number is less than or equal to the optimal value must be expressed. This probability can be calculated by the following equations:

$$P\{A_i \le A^{\max}\} = \frac{1}{n}\sum_{j=1}^{n} P\{V_{ij} \le A_j^{\max}\} \tag{29}$$

$$P(G_1 \le G_2) = \frac{\max[0, L^* - \max[0, \overline{G_1} - \underline{G_2}]]}{L^*} \tag{30}$$

$$L^* = L[G_1] + L[G_2] \tag{31}$$

(f) Ranking suppliers: Given the probabilities obtained in the previous step, any alternative having less distance from the ideal point is ranked higher.

3.4. Information fusion

The information fusion method is utilised to integrate the rankings obtained from two grey MCDM methods. Figure 1 shows the detailed steps required to implement

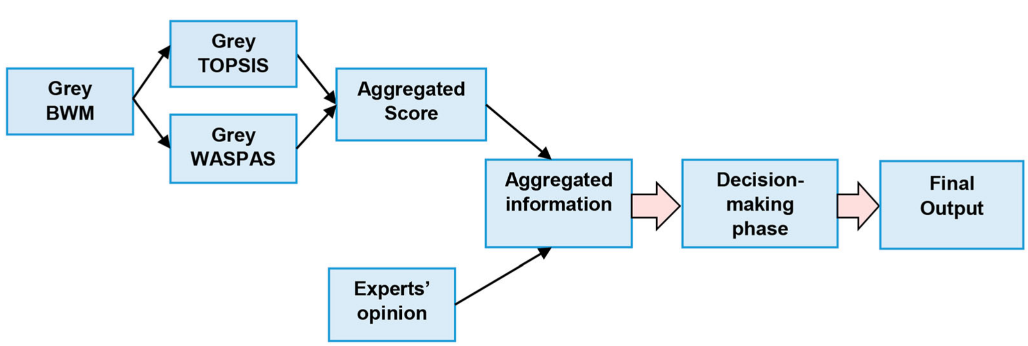

Figure 1. A graphical representation of the proposed Information fusion phase.

```
Information Fusion algorithm for grey-based MCDM methods for sustainable supplier selection
  Begin
 /* Extraction Phase/
Find the final ranks of the suppliers based on sustainable criteria;
        Find the final ranks of the suppliers in each sustainability section;
        Determine the best suppliers in each sustainability section for each grey-based algorithm;
        Put the selected suppliers into the aggregated pool of the best suppliers;
        Determine the best suppliers in the sustainable settings for each grey-based algorithm;
        Put the selected suppliers into the aggregated pool of the best suppliers;
/* End of Extraction phase /
Remove the repeated suppliers;
    /* Aggregation Phase/
Find the maximum value of scores for grey WASPAS;
Find the minimum value of scores for grey TOPSIS;
                Begin normalization
Calculated the normalized scores for grey WASPAS method;
                Calculated the normalized scores for grey TOPSIS method;
End
 Calculate the weighted scores of grey-based methods;
Begin experts' opinion aggregation
Collect the scores given to the suppliers in the pool by experts;
                Calculated the average score for each supplier;
                Find the maximum value of average scores;
Normalize the average scores;
End
      Calculate the total weighted scores of grey-based methods and experts' opinion;
      Sort the suppliers based on the total weighted scores;
      Find the final ranking of the best suppliers;
  /* End of aggregation phase /
End
```

Figure 2. Pseudo code of the information fusion algorithm.

this method for sustainable supplier evaluation and selection. Figure 2 demonstrates the pseudo-code for the proposed information fusion algorithm.

4. Case study

In this section, we present a case study to demonstrate the applicability and exhibit the efficacy of the proposed integrated framework. Intervan[1] is an automotive technology company located in Detroit, Michigan. The company builds electric sport utility vehicles and pickup trucks for sustainable transportation. Intervan is currently working on autonomous electric vehicles and an entire ecosystem of related products. The company has a large order for electric delivery vans from a major e-commerce company. As a result, the company is looking for suppliers of batteries for these delivery vans. Due to technical complexities and operational limitations, there are only five suppliers worldwide with the capability to provide the required amount of batteries. Intervan management needs to select one supplier among the available five suppliers considering sustainability. Intervan management defined several criteria in three pillars of sustainability and implemented the approach proposed in this study to achieve this goal. First, the weights of criteria are calculated using grey BWM. Then, a series of suppliers are evaluated based on the selected criteria. Finally, the experts' opinions are aggregated with the combined scores of the suppliers to derive a final ranking of the suppliers.

The sustainable supplier selection problem at Intervan consists of two phases. In phase 1, we choose a series of criteria in the three aspects of sustainability, including economic, social, and environmental. Expert opinions are then collected to find the relative importance of the criteria. This information is used to calculate the weights for the supplier selection criteria at Intervan. Next, the five suppliers of batteries for these delivery vans are evaluated based on these criteria. Figure 3 shows the proposed approach for sustainable supplier selection for Intervan.

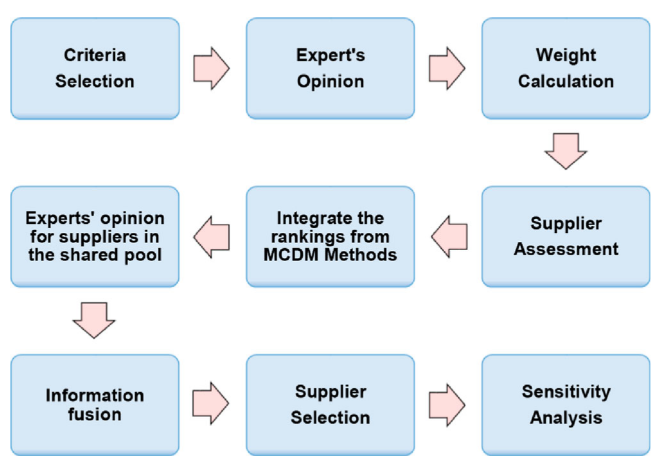

Figure 3. Proposed framework.

4.1. Criteria

The criteria are selected based on an extensive review of the sustainable supplier selection literature conducted by Nielsen et al. (2014). In addition, we added several criteria based on expert opinions. Table 4 provides a brief overview of the selected criteria in this study. A brief description of these criteria as well as their references in the literature is provided in this table. The assigned abbreviations for criteria are used in the upcoming sections of the article.

4.2. Supplier evaluation

Sustainable supplier selection is a multi-criteria problem. MCDM techniques can provide clear grounds for decision-makers to assess a series of suppliers to overcome the intricate nature of this problem. Since the investigated problem contains ambiguous information, integrating grey theory with novel MCDM techniques can result in more practical results, though. Therefore, in this study, a hybrid approach of two effective MCDM techniques, WASPAS and TOPSIS, and grey theory is

Table 4. The criteria in sustainable supplier selection.

Criterion	Abbreviation	Description	References
Cost	EC1	Consists of different elements such as production cost, ordering cost, and logistics cost.	Hashemi et al. (2015); Kannan (2018); Sarkis and Dhavale (2015); Büyüközkan and Çifçi (2012)
Quality	EC2	It can be measured through quality certifications as well as the rates of defection in final products.	Rajesh and Ravi (2015); Sarkis and Dhavale (2015); Hashemi et al. (2015); Tahriri et al. (2014)
Lead time	EC3	It mirrors the time between placement and arrival of an order.	Bai and Sarkis (2014); Govindan et al. (2013); Kuo et al. (2010)
Flexibility	EC4	The ability of a supplier to handle disruptions and respond to fluctuating demands.	Hashemi et al. (2015); Bai and Sarkis (2014); Govindan et al. (2013)
Production capability & facilities	EC5	It measures a supplier regarding machinery, Layout, and infrastructure facilities.	Tahriri et al. (2014); Grimm et al. (2014); Baskaran et al. (2012)
Financial position	EC6	It reflects the position of a supplier compared to its competitors in the market.	Yu and Hou (2016); Guarnieri et al. (2015); Büyüközkan and Çifçi (2012)
Brand*	EC7	It represents the public image of a supplier as a reputable business figure.	Lin et al. (2011)
Supportive Activities*	SO1	This criterion shows the supplier's ability to create a supportive atmosphere to engage and motivate its staff.	Fallahpour et al. (2017)
Employment Practices	SO2	This aspect is related to activities such as employee contracts, equity labour sources, and flexible working arrangements, all of which are related to working conditions of workers of a supplier.	Nikolaou et al. (2013); Kuo et al. (2010); Bai and Sarkis (2010)
Local Community Influence	SO3	It demonstrates the tangible effects of as supplier on its community. These effects can be categorised in health, education, economic welfare and growth, and supporting community projects segments.	Sarkis and Dhavale (2015); Govindan et al. (2013)
Development Commitment	SO4	This criterion measures the impact of a supplier on its local area in terms of creating providing financial prosperity as well as social equity.	Govindan et al. (2013); Nikolaou et al. (2013); Bai and Sarkis (2010)
Health & Safety Management System	SO5	This represents the efforts of the suppliers to guarantee the health and safety of workers at work.	Sarkis and Dhavale (2015); Wang (2010); Azadnia et al. (2012)
Pollution	EN1	It represents the emission rates of pollutant, waste water, solid wastes and other hazardous materials releases during normal activities of a supplier.	Tseng (2011); Shen et al. (2013); Azadnia et al. (2012)
Environmental Certifications	EN2	This criterion indicates the degree at which a supplier follows environmental regulations in different global certifications such as ISO 14001.	Chen et al. (2010)
Green Image	EN3	It reflects the public opinion about a supplier considering environmental aspects.	Kannan et al. (2015); Shen et al. (2013); Kannan et al. (2013); Lee et al. (2009);
Energy Consumption	EN4	It shows the resource consumption in terms of raw material, energy, and water during the routine activities of a supplier.	Erol et al. (2011); Govindan et al. (2013).
Eco-design	EN5	It assesses the supplier capability in designing products with lower consumption of material and energy. It also depicts the ability to produce products suitable for reuse, recycling and free of hazardous materials	Ji et al. (2016); Guarnieri et al. (2015); Shen et al. (2013)

implemented to assess and rank the suppliers in a clear and reliable way.

4.3. Weights calculation

The weights of the three sections of sustainability should be calculated by a linear grey BWM model to find the weights of the criteria. Before that, the best and the worst criteria must be selected based on experts' opinions. The relative importance of criteria is presented via a grey number. The average of three grey numbers is implemented in the model to obtain the final relative importance.

4.3.1. Highest level

At the highest level of the criteria, the weights of the three sections of sustainability should be calculated. Experts asserted that the economic and social criteria are the best and the worst ones at this level, respectively. Eq. (31) shows the relative importance of other sections to the best one. Table 5(a) provides the required information for the proposed grey BWM model. Eq. (32) and Table 5(b) demonstrate the numbers required, considering the worst criterion.

$$\begin{cases} a_B^1 = (1, H, H) \\ a_B^2 = (1, H, M) \\ a_B^3 = (1, H, M) \end{cases} \tag{31}$$

$$\begin{cases} a_W^1 = (H, 1, L) \\ a_W^2 = (M, 1, M) \\ a_W^3 = (M, 1, L) \end{cases} \tag{32}$$

Using the best and the worst vectors as inputs of the grey BWM model presented in Eqs. (1) to (6), the final weights of the three categories of criteria are presented in Table 5(c). The calculated IR shows the reliability of the final weights.

Table 5. Relative importance to the best and worst criteria along with the final weights at the highest level.

Criteria	Economic	Social	Environmental
5(a). Relative importance to the best criterion.			
First Expert	[1 1]	[6 8]	[6 8]
Second Expert	[1 1]	[6 8]	[4 6]
Third Expert	[1 1]	[6 8]	[4 6]
Average	[1 1]	[6 8]	[4.66 6.66]
5(b). Relative importance to the worst criterion			
First Expert	[6 8]	[1 1]	[2 4]
Second Expert	[4 6]	[1 1]	[4 6]
Third Expert	[4 6]	[1 1]	[2 4]
Average	[4.66 6.66]	[1 1]	[2.66 4.66]
5(c). Final weights			
Lower bound	0.6840442	0.07898894	0.1579779
Upper bound	0.8420221	0.07898894	0.1579779
Average weight	0.76303315	0.07898894	0.1579779

IR = 0.04701.

After having the weights of all the sections in the highest level of criteria, a similar procedure should be conducted to find the weights of the sub-criteria in each section.

4.3.2. Economic

A similar procedure to that of the top-level should be conducted in order to find the weights of the sub-criteria in this aspect. Cost and brand are the most and the least important criteria in this segment. Table 6(a) and 6(b) provide the required information for the proposed grey BWM model. Eqs. (33) and (34) show the relative importance of the criteria to the best and the worst one, respectively.

$$\begin{cases} a_B^1 = (1, M, H, H, VH, M, H) \\ a_B^2 = (1, H, H, VH, M, H, H) \\ a_B^3 = (1, M, M, H, VH, VH, VH) \end{cases} \tag{33}$$

$$\begin{cases} a_W^1 = (H, H, M, M, H, M, 1) \\ a_W^2 = (H, H, H, L, L, H, 1) \\ a_W^3 = (VH, H, M, L, L, L, 1) \end{cases} \tag{34}$$

Using the best and the worst vertices as inputs of the grey BWM model presented in Eqs. (1) to (6), the final weights of the sub-criteria in the economic aspect of sustainability are presented in Table 6(c). The obtained weights can be considered reliable since the IR is close enough to zero.

4.3.3. Social

A similar process should be conducted in order to find the weights of the social aspect sub-criteria. Supportive activities and employment practices are the most and the least influential criteria in this aspect based on experts' opinions. Table 7(a) and 7(b) provides the required information for the proposed grey BWM model. Eqs. (35)–(36) are the relative importance of criteria to the best and the worst one, respectively.

$$\begin{cases} a_B^1 = (1, H, L, H, M) \\ a_B^2 = (1, M, M, VH, VH) \\ a_B^3 = (1, H, M, H, VH) \end{cases} \tag{35}$$

$$\begin{cases} a_W^1 = (H, 1, M, M, H) \\ a_W^2 = (M, 1, VH, VH, M) \\ a_W^3 = (H, 1, M, L, L) \end{cases} \tag{36}$$

Using the best and the worst vertices as inputs of the grey BWM model presented in Eqs. (1) to (6), the final

Table 6. Relative importance to the best and worst criteria along with the final weights in the economic section.

Criteria	EC1	EC2	EC3	EC4	EC5	EC6	EC7
6(a). Relative importance to the best criterion.							
First Expert	[1 1]	[4 6]	[6 8]	[6 8]	[8 10]	[4 6]	[6 8]
Second Expert	[1 1]	[6 8]	[6 8]	[8 10]	[4 6]	[6 8]	[6 8]
Third Expert	[1 1]	[4 6]	[4 6]	[6 8]	[8 10]	[8 10]	[8 10]
Average	[1 1]	[4.66 6.66]	[5.33 7.33]	[7.33 9.33]	[6.66 8.66]	[6 8]	[6.66 8.66]
6(b). Relative importance to the worst criterion.							
First Expert	[6 8]	[6 8]	[4 6]	[4 6]	[6 8]	[4 6]	[1 1]
Second Expert	[6 8]	[6 8]	[6 8]	[2 4]	[2 4]	[6 8]	[1 1]
Third Expert	[8 10]	[6 8]	[4 6]	[2 4]	[2 4]	[2 4]	[1 1]
Average	[6.66 8.66]	[6 8]	[4.66 6.66]	[2.66 4.66]	[3.33 5.33]	[4 6]	[1 1]
6(c). Final weights.							
Lower bound	0.4571282	0.1101981	0.1001254	0.07866231	0.08474819	0.09173992	0.03869893
Upper bound	0.534526	0.1101981	0.1001254	0.07866231	0.08474819	0.09173992	0.03869893
Average weight	0.4958271	0.1101981	0.1001254	0.07866231	0.08474819	0.09173992	0.03869893

IR = 0.04461.

Table 7. Relative importance to the best and worst criteria along with the final weights in the social section.

Criteria	SO1	SO2	SO3	SO4	SO5
7(a). Relative importance to the best criterion.					
First Expert	[1 1]	[6 8]	[2 4]	[6 8]	[4 6]
Second Expert	[1 1]	[4 6]	[4 6]	[8 10]	[8 10]
Third Expert	[1 1]	[6 8]	[4 6]	[6 8]	[8 10]
Average	[1 1]	[5.33 7.33]	[3.33 5.33]	[6.66 8.66]	[6.66 8.66]
7(b). Relative importance to the worst criterion.					
First Expert	[6 8]	[1 1]	[4 6]	[4 6]	[6 8]
Second Expert	[4 6]	[1 1]	[8 10]	[8 10]	[4 6]
Third Expert	[6 8]	[1 1]	[4 6]	[2 4]	[2 4]
Average	[5.33 7.33]	[1 1]	[5.33 7.33]	[4.66 6.66]	[4 6]
7(c). Final weights.					
Lower bound	0.527029	0.052426	0.165006	0.101557	0.101557
Upper bound	0.631881	0.052426	0.165006	0.101557	0.101557
Average weight	0.579455	0.052426	0.165006	0.101557	0.101557

IR = 0.05540.

weights of the sub-criteria in the social aspect of sustainability are presented in Table 7(c). The IR of this section is acceptable, too.

4.3.4. Environmental

A procedure similar to the one used for the social and economic aspects should be followed to find the weights

Table 8. Relative importance to the best and worst criteria along with the final weights in the environmental section.

Criteria	EN1	EN2	EN3	EN4	EN5
8(a). Relative importance to the best criterion.					
First Expert	[1 1]	[6 8]	[8 10]	[4 6]	[4 6]
Second Expert	[1 1]	[4 6]	[6 8]	[2 4]	[2 4]
Third Expert	[1 1]	[6 8]	[6 8]	[2 4]	[4 6]
Average	[1 1]	[5.33 7.33]	[6.66 8.66]	[2.66 4.66]	[3.33 5.33]
8(b). Relative importance to the worst criterion.					
First Expert	[8 10]	[2 4]	[1 1]	[4 6]	[4 6]
Second Expert	[6 8]	[4 6]	[1 1]	[4 6]	[2 4]
Third Expert	[6 8]	[6 8]	[1 1]	[2 4]	[2 4]
Average	[6.66 8.66]	[4 6]	[1 1]	[3.33 5.33]	[2.66 4.66]
8(c). Final weights.					
Lower bound	0.492989	0.104508	0.047196	0.164388	0.143724
Upper bound	0.587381	0.104508	0.047196	0.164388	0.143724
Average weight	0.540185	0.104508	0.047196	0.164388	0.143724

IR = 0.03997.

of the environmental factors. Pollution and green images are the best and the worst criteria based on experts' opinions. Table 8(a) and 8(b) provide the required information for the proposed grey BWM model. Eqs. (37) and (38) show the relative importance of criteria to the best and the worst one, respectively.

$$\begin{cases} a_B^1 = (1, H, VH, M, M) \\ a_B^2 = (1, M, H, L, L) \\ a_B^3 = (1, H, H, L, M) \end{cases} \quad (37)$$

$$\begin{cases} a_W^1 = (VH, L, 1, M, M) \\ a_W^2 = (H, M, 1, M, L) \\ a_W^3 = (H, H, 1, L, L) \end{cases} \quad (38)$$

Using the best and the worst vertices as inputs of the grey BWM model presented in Eqs. (1) to (6), the final weights of the sub-criteria in the environmental aspect of sustainability are presented in Table 8(c). The IR of this section is also within the acceptable range.

4.3.5. Final weights

Table 9 demonstrates the final weights of all the criteria by which the suppliers should be evaluated.

4.4. Supplier evaluation

In the next step, the suppliers should be scored in each criterion. The attributed grey linguistic scores are presented in Table 10. Table 11 shows the scores of the suppliers in each criterion.

4.5. Grey WASPAS

The data of Table 11 is used in Eqs. (7) to (21) to achieve the final ranking of the suppliers. Figure 4(a), 4(b), and 4(c) shows the ranking of the suppliers considering the economic, social, and environmental criteria separately. Figure 4(d) demonstrates the final ranking of the suppliers using all the criteria. As is stated above, the higher index of a supplier indicates a better status of the supplier compared to others.

Table 9. Final weights of the criteria.

Criteria		$\underline{w_j}$	$\overline{w_j}$	Average weight
Economic	EC1	0.312696	0.450083	0.378332
	EC2	0.07538	0.092789	0.084085
	EC3	0.06849	0.084308	0.076399
	EC4	0.053808	0.066235	0.060022
	EC5	0.057971	0.07136	0.064666
	EC6	0.062754	0.077247	0.070001
	EC7	0.026472	0.032585	0.029529
Social	SO1	0.04163	0.049912	0.045771
	SO2	0.004141	0.004141	0.004141
	SO3	0.013034	0.013034	0.013034
	SO4	0.008022	0.008022	0.008022
	SO5	0.008022	0.008022	0.008022
Environmental	EN1	0.077881	0.092793	0.085337
	EN2	0.01651	0.01651	0.01651
	EN3	0.007456	0.007456	0.007456
	EN4	0.02597	0.02597	0.02597
	EN5	0.022705	0.022705	0.022705

Table 10. Grey linguistic intervals.

Interval	Linguistic
[0,2]	Very Poor
[2,4]	Poor
[4,6]	Good
[6,8]	Very Good
[8,10]	Excellent

4.6. Grey TOPSIS

The data of Table 11 is used in Eqs. (22) to (31) to achieve the final ranking of the suppliers. Figure 5(a), 5(b), and 5(c) show the separate ranking of the suppliers, and Figure 5(d) shows the final ranking via the proposed grey TOPSIS method. In this method, the lower probability of a supplier indicates a better status of the supplier compared to others.

4.7. Information fusion phase

In this section, we describe the proposed information fusion process used at Intervan.

4.7.1. Extraction phase

In this phase, the best suppliers proposed by each algorithm are compiled in a list. These best suppliers include the top suppliers in the individual pillars of sustainability, as well as the top three suppliers in the overall evaluation. Figure 6 shows a graphical representation of this process.

4.7.2. Aggregation phase

In this phase, we aggregate the results from two proposed algorithms for the final pool of the chosen suppliers. Before proceeding with the process, the scores obtained from the proposed methods are normalised. However, since the nature of scores differs in grey TOPSIS and grey WASPAS, the normalisation methods are somehow different. Eqs. (39) and (40) show the required normalisation process for the grey WASPAS and grey TOPSIS, respectively. Following the normalisation process, the weighted scores are calculated by considering an equal weight of 0.5 for each method in Eq. (41). Tables 12 and 13 show the score of the best suppliers in each grey

Table 11. Score of suppliers in each criterion.

Criteria	Economic							Social					Environmental				
Supplier	EC1	EC2	EC3	EC4	EC5	EC6	EC7	SO1	SO2	SO3	SO4	SO5	EN1	EN2	EN3	EN4	EN5
S1	*P*	*P*	E	*P*	VG	*P*	*P*	*P*	VG	*P*	*P*	*P*	G	E	*P*	VG	G
S2	*P*	VG	G	VG	VG	*P*	*P*	E	*P*	VG	E	*P*	*P*	E	E	*P*	E
S3	*P*	*P*	G	E	*P*	*P*	G	VG	VG	E	E	*P*	*P*	*P*	E	*P*	VG
S4	G	*P*	*P*	G	E	G	*P*	E	E	G	VG	VG	*P*	G	G	G	E
S5	*P*	*P*	*P*	*P*	VG	G	VG	E	*P*	E	VG	E	VG	VG	*P*	E	*P*
S6	E	VG	VG	E	*P*	E	*P*	VG	G	VG	*P*	*P*	E	VG	G	*P*	G
S7	G	VG	E	*P*	*P*	*P*	*P*	VG	E	VG	E	VG	VG	G	*P*	E	E
S8	VG	G	*P*	VG	*P*	G	*P*	*P*	E	E	VG	VG	VG	VG	VG	G	VG
S9	G	E	G	*P*	E	G	*P*	E	VG	G	*P*	VG	E	E	E	E	G
S10	VG	*P*	VG	*P*	G	VG	G	G	*P*	VG	E	*P*	E	E	E	E	*P*
S11	G	VG	G	VG	G	E	*P*	G	*P*	G	VG	*P*	E	E	G	G	*P*
S12	*P*	E	*P*	G	*P*	*P*	*P*	G	*P*	VG	*P*	*P*	VG	*P*	VG	G	VG
S13	G	G	*P*	G	*P*	G	*P*	*P*	VG	VG	G	E	*P*	E	G	VG	VG
S14	G	*P*	E	E	G	*P*	G	G	E	*P*	E	E	E	*P*	E	E	G
S15	*P*	*P*	*P*	E	E	E	VG	*P*	G	*P*	E	G	*P*	VG	G	*P*	VG
S16	VG	E	E	E	E	VG	*P*	G	*P*	*P*	VG	*P*	VG	G	*P*	G	VG
S17	*P*	E	VG	*P*	G	G	*P*	E	G	*P*	E	*P*	VG	VG	*P*	*P*	E
S18	*P*	*P*	*P*	G	G	*P*	*P*	*P*	*P*	E	E	VG	E	VG	E	*P*	E
S19	E	VG	VG	*P*	VG	*P*	E	E	E	E	E	*P*	G	*P*	G	VG	VG
S20	*P*	G	VG	*P*	E	*P*	G	E	*P*	E	E	E	*P*	G	VG	E	VG
S21	E	*P*	*P*	E	E	G	E	G	G	E	E	G	E	E	VG	G	*P*
S22	*P*	G	E	G	*P*	G	*P*	G	E	E	E	VG	E	*P*	VG	G	*P*
S23	VG	*P*	*P*	G	G	E	*P*	E	VG	*P*	G	VG	G	G	E	G	E
S24	VG	E	VG	VG	E	G	G	E	*P*	VG	E	G	E	*P*	E	E	G
S25	G	*P*	G	E	G	*P*	VG	E	*P*	VG	G	VG	VG	E	E	*P*	G
S26	G	*P*	*P*	*P*	*P*	VG	E	VG	G	E	G	VG	VG	*P*	VG	*P*	VG
S27	*P*	G	E	G	E	*P*	*P*	E	G	VG	*P*	E	G	VG	VG	E	G
S28	G	VG	*P*	G	E	*P*	E	*P*	G	G	G	E	VG	VG	E	E	E
S29	E	G	*P*	*P*	*P*	*P*	VG	*P*	E	G	VG	E	E	G	*P*	*P*	*P*
S30	*P*	VG	*P*	E	*P*	VG	VG	E	E	E	E	*P*	G	G	G	*P*	E

MCDM method and their average scores, respectively.

$$S_{GW}^{N} = \frac{S_i}{\max(S_i)} \tag{39}$$

$$S_{GT}^{N} = \frac{\min(S_i)}{S_i} \tag{40}$$

$$WS_i = W_{GW} \times S_{GW}^{N} + W_{GT} \times S_{GT}^{N} \tag{41}$$

Given the weighted average scores for each supplier and each method, we consider the ones with the higher scores as the more desirable options. Next, we asked the experts to assign a score from 1 to 10 to each supplier in the pool. Then, the scores were averaged and normalised. Eq. (42) is used to normalise the scores of the experts. The scores assigned to the most suitable suppliers are provided in Table 14.

$$ES_i = \frac{ES_i}{\max(ES_i)} \tag{42}$$

In the final step of this phase, we combine the normalised scores of the grey MCDM methods with expert opinions using Eq. (43). It is assumed that both parts have the same gravity in the final score (equal weight of 0.5).

$$WS_i = W_{Exp} \times SE_i^{N} + W_{GM} \times S_{GM}^{N} \tag{43}$$

Next, we use the weighted scores and obtain the final ranking of the suppliers based on the higher total score shown in Table 15. Figure 7 presents the total weighted score of the most desirable suppliers.

4.8. Sensitivity analysis

The sensitivity analysis reflecting different aspects of the proposed framework includes two sections. In the first part, the focus is on the impact of changes in the weights on the output of the grey-based methods. The second sector is related to monitoring the emerging patterns from variation in the weights of the grey-based methods and experts in the final output of the information fusion and final ranking of the best options.

4.8.1. Grey MCDM methods

As the pairwise comparisons are based on human judgments, they are prone to dramatic changes. One way for dealing with these variations is by using possible scenarios in order to assess the robustness of the proposed method. Since the weights of the sub-criteria are affected by the possible changes at the highest level of sustainability, four scenarios are defined based on changes in the weights of the three sections of sustainability. Likewise, the relative importance of decision-makers is prone to change. Therefore, Scenarios 8–15 are defined to assess the impact of these variations on the final ranking of the suppliers. Scenarios 5–7 are extreme situations in

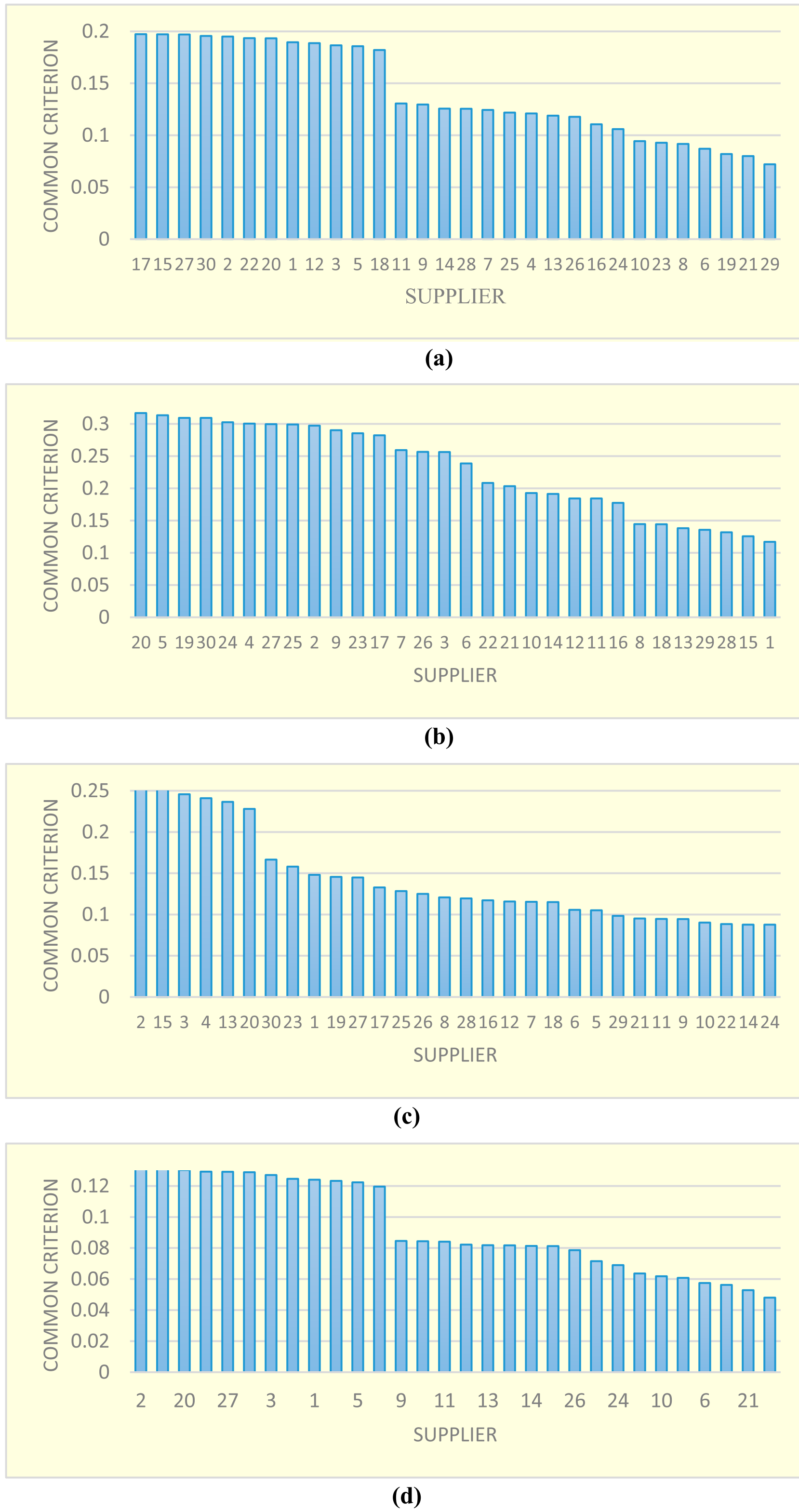

Figure 4. The economic, social, environmental, and final ranking of suppliers with grey WASPAS. 4(a). Economic criteria 4(b). Social criteria; 4(c). Environmental criteria; 4(d). The final ranking of the grey WASPAS method.

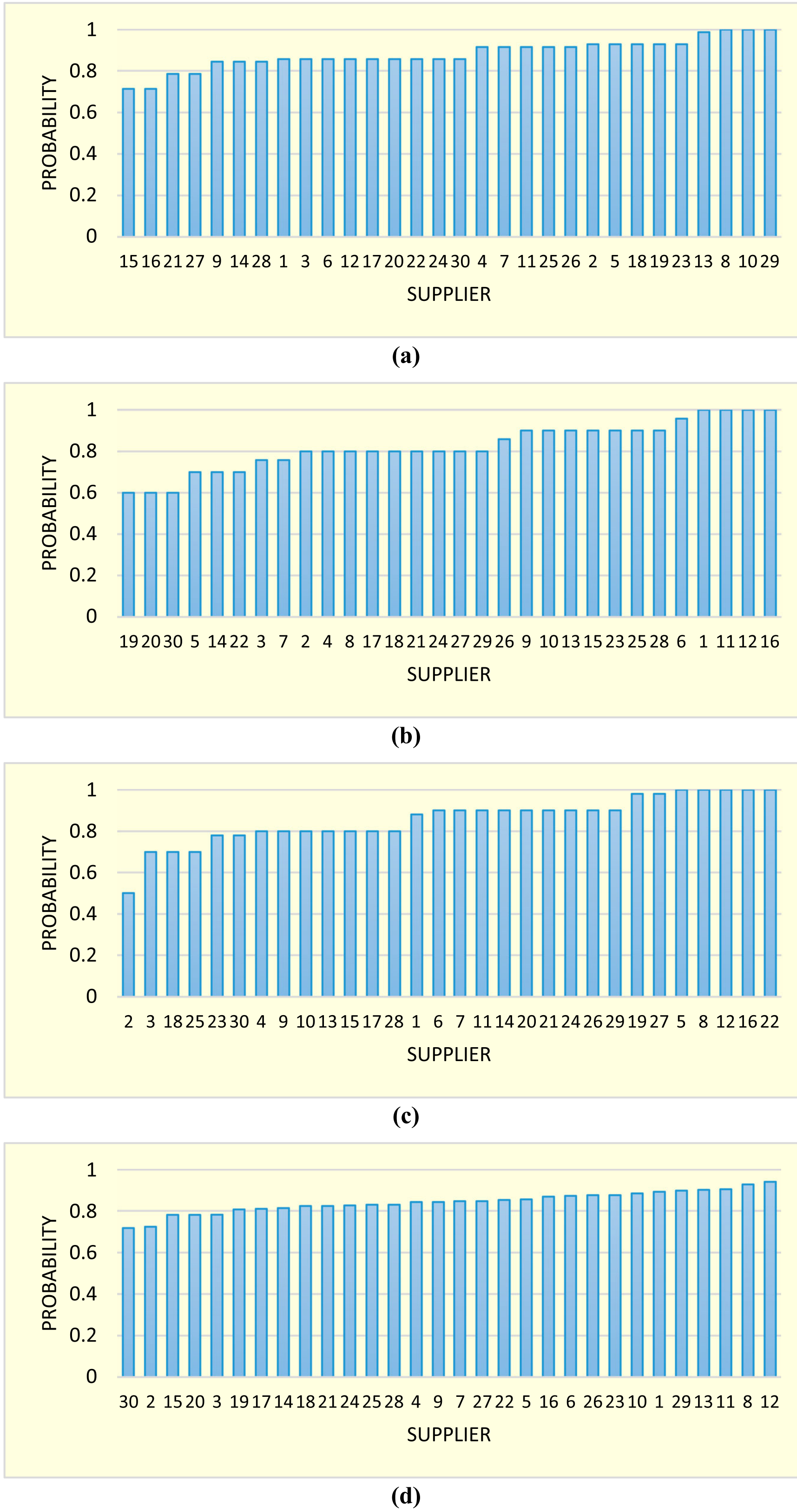

Figure 5. The economic, social, environmental, and final ranking of suppliers with grey TOPSIS. 5(a). Economic criteria; 5(b). Social criteria; 5(c). Environmental criteria; 5(d). The final ranking of the grey TOPSIS method.

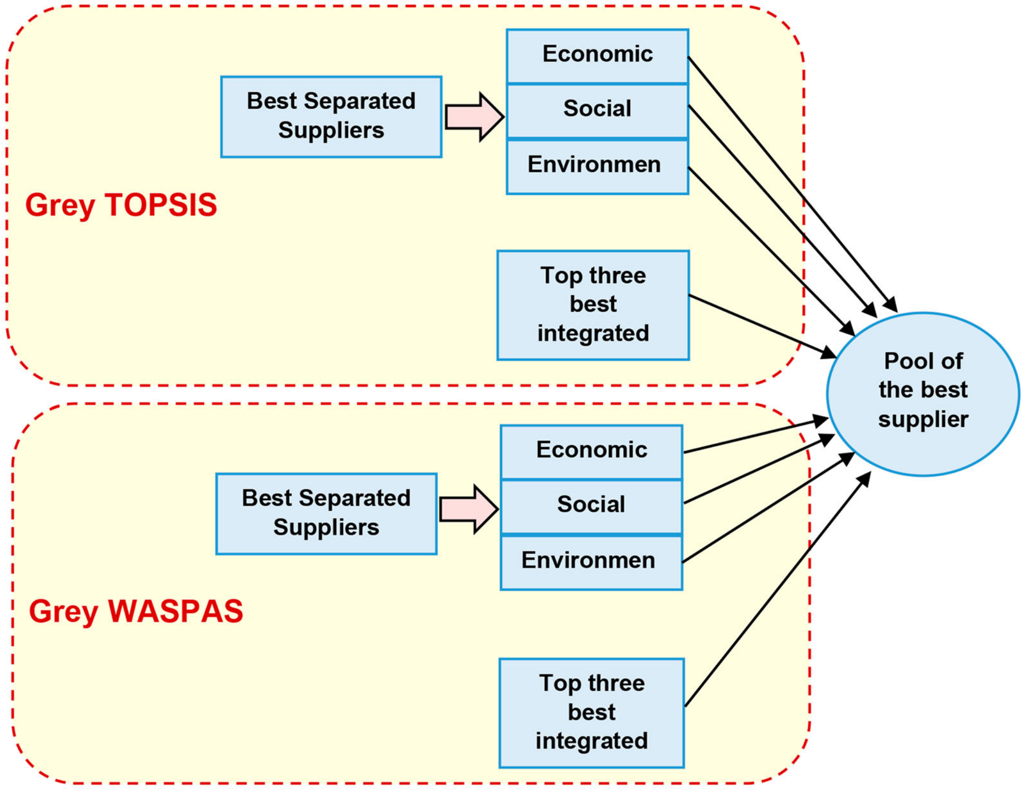

Figure 6. Proposed information fusion steps.

Table 12. Score of best suppliers for each grey MCDM method.

Supplier index	Grey WASPAS	Grey TOPSIS
17	0.1288	0.8102
15	0.130938	0.7808
20	0.130287	0.7808
19	0.056277	0.8071
2	0.13197	0.7247
30	0.129212	0.7188

Table 13. Average scores of the most suitable suppliers.

	Normalised score		
Supplier index	Grey WASPAS	Grey TOPSIS	Average scores
17	0.975976	0.887188	0.931582031
15	0.992175	0.920594	0.956384872
20	0.987242	0.920594	0.953917893
19	0.426439	0.890596	0.658517486
2	1	0.991859	0.99592935
30	0.9791	1	0.989550152

Table 14. Expert scores for the most suitable suppliers.

	Expert				
Supplier index	1	2	3	Average score	Normalised score
17	4	1	4	3	0.333
15	6	7	4	5.667	0.629
20	5	6	6	5.667	0.629
19	3	3	2	2.667	0.296
2	8	8	10	8.667	0.962
30	8	10	9	9	1

which only one aspect of sustainability is considered in the supplier selection process.

Table 16 provides the final rankings of the suppliers in each scenario via the proposed integrated methods. The results of the sensitivity analysis phase mirror that different scenarios can change the sequence of the suppliers. The outputs of the proposed grey WASPAS method show that in the scenarios considering all the criteria, the ranking of the suppliers is not very different. S2 is the best supplier in many cases, while the next rankings are more varied. Supplier 15 and supplier 20 are the next suitable suppliers in these scenarios. However, considering the economic criteria solely, led to a different ranking in which supplier 17 is the best one, and supplier 2 is the fifth supplier. This difference can be justified by the fact that supplier 2 is the best one in scenario 7 considering environmental criteria separately, while supplier 17 is not among the top 5 suppliers. This superiority in the environmental section can compensate for the difference in the economic aspect. In addition, it is interesting that while all the top suppliers in scenario 5 are among the high ranked ones in other cases, in scenarios 6 and 7, only 2 of the top suppliers are among the highest ranks in scenarios with all the criteria. This can indicate that, despite a growing interest in including social and environmental criteria in sustainable supplier selection, decision-makers

Table 15. Final Scores and rankings of the most suitable suppliers.

Supplier index	Grey based methods	Experts' opinion	Total weighted score	Final ranking
17	0.931582	0.333333333	0.632457682	5
15	0.956385	0.62962963	0.793007251	3
20	0.953918	0.62962963	0.791773762	4
19	0.658517	0.296296296	0.477406891	6
2	0.995929	0.962962963	0.979446157	2
30	0.98955	1	0.994775076	1

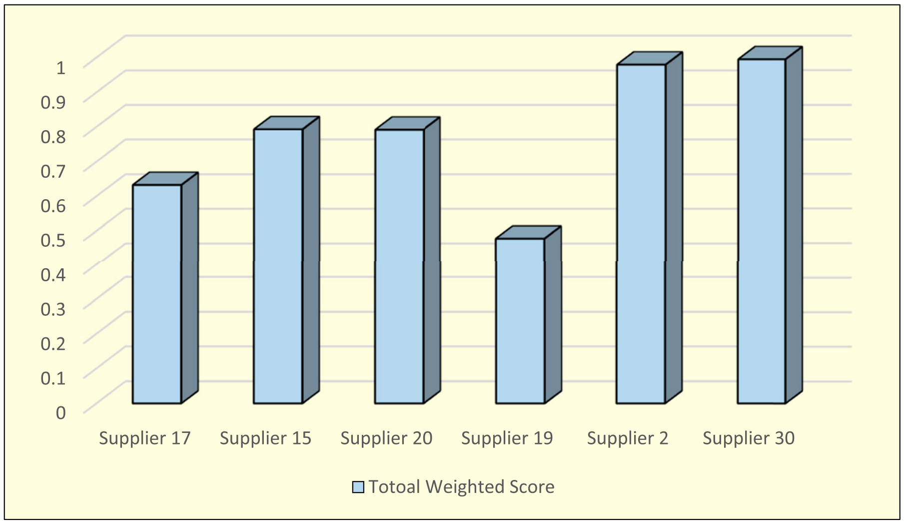

Figure 7. Total weighted scores of the best suppliers.

Table 16. Final rankings of the suppliers in different scenarios.

Scenario	Criteria	Weights of experts	Grey WASPAS	Grey TOPSIS
1	All criteria	All equal	2 > 15 > 20 > 3 > 30	30 > 2 > 20 > 15 > 3
2	All criteria	All equal	2 > 15 > 20 > 3 > 30	30 > 2 > 15 > 20 > 3
3	All criteria	All equal	2 > 20 > 30 > 27 > 17	30 > 2 > 15 > 20 > 3
4	All criteria	All equal	2 > 20 > 30 > 27 > 17	30 > 2 > 20 > 15 > 3
5	Economic only	All equal	17 > 15 > 27 > 30 > 2	15 > 16 > 21 > 27 > 9
6	Social only	All equal	20 > 5 > 19 > 30 > 24	19 > 20 > 30 > 5 > 14
7	Environmental Only	All equal	2 > 15 > 3 > 4 > 13	2 > 3 > 18 > 25 > 23
8	All criteria	$E1$	15 > 30 > 2 > 17 > 20	30 > 2 > 15 > 20 > 3
9	All criteria	$E2$	15 > 2 > 20 > 27 > 17	30 > 2 > 15 > 20 > 3
10	All criteria	$E3$	2 > 20 > 27 > 17 > 15	30 > 2 > 15 > 20 > 3
11	All criteria	$E1(0.25)E2(0.5)E3(0.25)$	2 > 15 > 20 > 27 > 30	30 > 2 > 15 > 20 > 3
12	All criteria	$E1(0.4)E2(0.4)E3(0.2)$	2 > 15 > 20 > 30 > 27	30 > 2 > 15 > 20 > 3
13	All criteria	$E1(0.5)E2(0.3)E3(0.2)$	2 > 15 > 20 > 30 > 27	30 > 2 > 15 > 20 > 3
14	All criteria	$E1(0.3)E2(0.4)E3(0.3)$	2 > 15 > 20 > 30 > 27	30 > 2 > 15 > 20 > 3
15	All criteria	$E1(0.2)E2(0.4)E3(0.4)$	2 > 15 > 20 > 27 > 30	30 > 2 > 15 > 20 > 3

still do not attribute high significance to those criteria compared to economic ones such as cost or quality.

As is shown in Table 9, the weight of the economic sections is almost 10 and 4 times higher than that of social and environmental segments, respectively. Moreover, the final rankings of scenarios 8–10 demonstrate that different experts had different opinions about the suppliers. This can highlight the need for having the opinions of several experts in supplier selection problems in order to eliminate the natural variations in human judgments. On the other hand, the results of the proposed grey TOPSIS are more consistent in different scenarios. This feature might stem from the fact that this method is less sensitive to small variations in the weights of the criteria. However, in scenarios 5–7 when only one aspect of sustainability is considered, the rankings are quite different from other scenarios. In contrast, considering the opinions of each expert separately in scenarios 8–10 did not affect the original ranking of the suppliers in this method. Changing the weights of decision-makers did not change the ranking of suppliers either.

4.8.2. Information fusion method

Several scenarios are defined based on different combinations of the weights of the methods and expert opinions in the final stage of the process to test the reliability and

Table 17. Final scores and rankings of the most suitable suppliers in different scenarios.

Scenario	Algorithm weights	Expert weights
1	0.9	0.1
2	0.8	0.2
3	0.7	0.3
4	0.6	0.4
5	0.4	0.6
6	0.3	0.7
7	0.2	0.8
8	0.1	0.9

robustness of our results. Table 17 shows the scenarios and the respected weights for both sections.

The process is carried out for each scenario, and the results are demonstrated in Figure 8. The proposed information fusion method produces reliable and robust results in most cases with the exception of the case where a high weight is assigned to the algorithms part of the final score. The final ranking of all the other suppliers remains unchanged in all the scenarios.

4.9. Managerial implications

The integrated information fusion and grey MCDM framework proposed in this study have several managerial implications. Firstly, it provides an effective method for sustainable supplier selection, considering imprecise information for managers. Decision-makers can implement the proposed method in a range of industrial settings from single production facilities, interconnected networks of plants to global supply chains to select the most suitable suppliers. Not only these business entities will benefit economically from this supplier selection process, but also, they can establish long-term relations with suppliers, which consider social and environmental criteria as well as economic ones in their routine activities. Furthermore, supplier organisations can utilise the proposed method to improve their status in terms of producing green products, being socially responsible toward society, and presenting their services at a reasonable cost. This will improve their chance of selection in the supplier selection process leading to more profound business relations with their customers. The results of such an approach can be increasing product quality, reducing cost and reducing or eliminating environmentally pollutant materials in the supply chain, and finally enhancing the market share. Finally, considering grey numbers in the proposed method will provide some relaxation in the decision-making process. Since some information is naturally susceptible to small variations, managers will have a useful tool to deal with these alterations. Likewise, supplier organisations can include some flexibility in their activities to respond to their orders more effectively.

The results of the proposed framework will enable companies to choose the most eligible suppliers among several candidates. Companies might end their business relations with suppliers, which are not strong enough compared to others or demand tangible improvements regarding the most important criteria, such as cost or pollution control. However, stopping business interactions with some suppliers is inevitable. Moreover, the proposed approach helps managers to reduce the risk of assigning orders to suppliers since suppliers are evaluated based on a set of criteria. Therefore, managers can assign their orders to the suppliers with the highest ranking and use sensitivity analysis to make the best decision in case of a possible change in their business priorities.

5. Conclusion

The supplier selection is becoming a more and more challenging decision for decision-makers in supply chains.

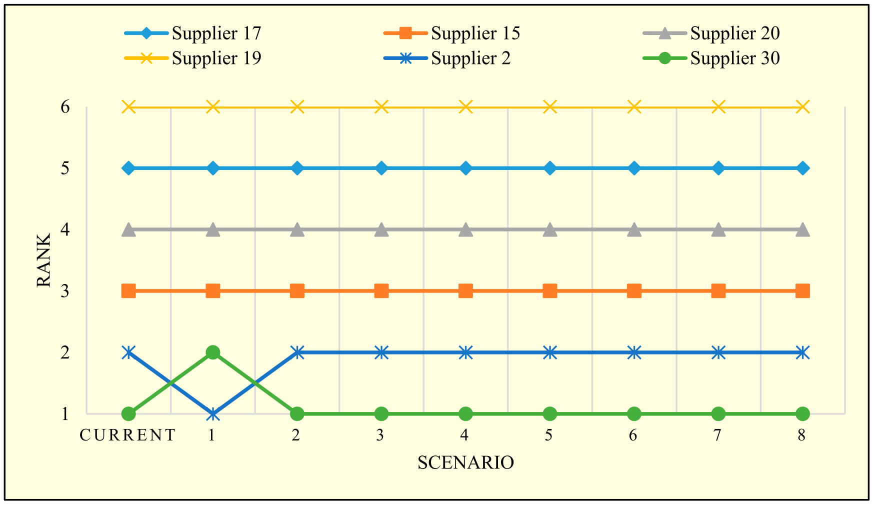

Figure 8. Supplier ranking in each scenario.

Not only should they consider economic criteria in their decisions, but they must also include social and environmental aspects. As a result, the sustainability notion has gained much more attention from researchers and practitioners in recent decades. Moreover, new intricate networks of suppliers, retailers, and final customers result in more ambiguous information. Therefore, in this paper, a sustainable supplier selection problem with a grey theory approach to handle the imprecise information was investigated. A case study is presented to demonstrate the applicability of the proposed method and exhibit the efficacy of the algorithms proposed in this study. At first, a set of criteria was selected from the literature. Then, their weights were calculated via a novel grey BWM approach. Then, a score is assigned to each supplier in each criterion. Two integrated approaches were implemented, grey WASPAS and grey TOPSIS, to rank the suppliers with this input information. The information fusion algorithm was used to ensure the inputs from the grey MCDM methods, and expert opinions have an equal impact on the final ranking of the suppliers. Finally, a sensitivity analysis is conducted to assess the effectiveness of the proposed approaches. To do so, 15 different scenarios were defined, and the ranking is obtained in all those scenarios. Eight scenarios were compared to assess the reliability and robustness of the information fusion method. The contributions of this study can be summarised as follows:

- We used the weighting scheme of a grey BWM weighting in the grey WASPAS and grey TOPSIS for ranking the suppliers and used the outputs of these two methods as input in an information fusion procedure.
- For the first time, we proposed a novel double-sided information fusion procedure in which we create a shortlist of the best suppliers based on the output of a combined grey BWM and grey TOPSIST, and a combined grey BWM and grey WASPS. We then integrate the rankings produced by the two combined methods. Finally, the experts' opinions are injected into the information fusion framework to produce a unified ranking of the suppliers.

This study has some limitations that are the foundations for future research directions. One of the limitations of this study is that it considers just one method for finding the weights of all the criteria. It would be productive for future researchers to use different methods for finding the weights when there is imprecise information and making a comparative analysis of these methods. Although we did an extensive search for selecting all the criteria for each subsection of sustainability, it would be valuable for future papers to consider new criteria for each subsection. Another possible opportunity for further research is to apply the proposed information fusion framework with more algorithms and to a large-scale group decision-making problem. Moreover, it would be useful for researchers to propose new methods for tackling MCDM problems, especially when some of the parameters are uncertain. Future studies can also focus on simultaneously solving the supplier selection problem with other problems like portfolio optimisation, which are interconnected. Another essential direction that can be taken by researchers is proposing new measurements for calculating the reliability of MCDM approaches. In addition to our proposed methods in this paper, other MCDM methods can be employed in a grey environment.

Note

1. The name is changed to protect the anonymity of the company.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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