Annals of Operations Research (2021) 296:335–362
https://doi.org/10.1007/s10479-020-03611-x

S.I. : MOPGP 2017

Gresilient supplier assessment and order allocation planning

Ahmed Mohammed[1] · Irina Harris[2] · Anthony Soroka[2] · Mohamed Naim[2] · Tim Ramjaun[2] · Morteza Yazdani[3]

Published online: 21 April 2020

Abstract
Companies are under pressure to re-engineer their supply chains to 'go green' while simultaneously improving their resilience to cope with unexpected disruptions where the supplier selection decision plays a strategic role. We present a new approach to supplier evaluation and allocating the optimal order quantity from each supplier with respect to green and resilience (gresilience) characteristics. An integrated framework that considers traditional business, green and resilience criteria and sub-criteria was developed, followed by a calculation of importance weight of criteria and sub-criteria using analytical hierarchy process (AHP). We evaluate suppliers using the technique for order of preference by similarity to ideal solution (TOPSIS). The obtained weights from AHP and TOPSIS were integrated into a developed multi-objective programming model used as an order allocation planner and the ε-constraint method was used to solve the multi-objective optimization problem. TOPSIS was applied to select the final Pareto solution based on its closeness from the ideal solution. The applicability and effectiveness of the proposed approach was illustrated using a real case study through a comparatively meaningful ranking of suppliers. The study provides a helpful aid for managers seeking to improve their supply chain resilience along with 'go green' responsibilities.

Keywords Green development · Supply chain resilience · Supplier selection · AHP · TOPSIS · Multi-objective optimization

Abbreviations

TGR	Traditional green resilience
QFD	Quality function deployment
ANP	Analytic network process
ANN	Artificial neural network
DEA	Data envelopment analysis
FAD	Fuzzy axiomatic design
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje

✉ Ahmed Mohammed
amm.alhamdany@gmail.com

Extended author information available on the last page of the article

1 Introduction

The supplier selection decision-making process is a fundamental activity in supply chain management, since purchasing costs account for more than fifty percent of all firms' expenses (Khan et al. 2018; Chang 2017). Supplier selection is often a complex, multi-criteria decision-making problem that requires thorough performance evaluation to create the most efficient supply network. Despite the financial imperative, other evaluation criteria should be considered such as reliable delivery, which can enhance production flow and decrease the overall (operational) cost. Dickson (1966) highlighted 23 criteria that can be considered by decision makers for supplier assessment, Ha and Krishnan (2008) expanded on this work, totalling 30. However, the most popular traditional business criteria are quality, cost, and delivery reliability; the most popular green criteria are: environmental management system, resource consumption, eco-design and waste management. Further supplier selection criteria can be found in Weber et al. (1991); Govindan et al. (2015); Mohammed 2020; Aissaoui et al. (2007) and Lorenc and Lerher (2019).

With the recognition of resource depletion, companies are ever increasingly required to consider the environmental impact of their supply chain (Koberg and Longoni 2018; Rezaei et al. 2017; Nujoom et al. 2018, 2019; Mohammed and Wang 2017; Mohammed et al. 2019a, b). Green supply chain management understands and accounts for the full range of purchasing, production, marketing, packaging and logistical activities from an environmental perspective (Burinskiene et al. 2018; Mohammed et al. 2018a, b; Sarkis 1999). Unfortunately, suppliers typically represent inevitable sources of external risk (Alikhani 2018; Jamshidi et al. 2018; Kaur and Singh 2016). It has been indicated that purchasing managers consider traditional and recently green criteria when assessing suppliers but neglecting resilience aspects (Ivanov 2017; Kannan et al. 2013). Christopher and Peck (2004) defined supply chain resilience "the ability of a [supply chain] to return to its original state or move to a new, more desirable state after being disturbed". Resilience which was also defined as the capability of a system to efficiently adopt expected disruptions and back to its normal process, is a vital aspect of any supply chain management (Torabi et al. 2015). During the Japanese earthquake (2011), Apple's iPad 2 production was negatively affected due to a lack of flash memory and super-thin battery (BBC News, 18 Mar 2011). This event also interrupted the automotive sector and retail supply chains in the UK (Hall, 16 Apr 2010). Recently, hurricane Sandy led to massive disruptions in US supply networks (Ortega and Taşpınar 2018; Torabi et al. 2015). Therefore, designing a resilient supply chain is necessary to protect a business from unexpected events (Sáenz et al. 2018). Resilience criteria are mainly represented by a supplier's capability to cope with risk and unexpected events more efficiently and quickly than other suppliers. The current work considers resilience criteria identified and analysed by Purvis et al. (2016). The work proposed a framework for the development and implementation of a resilient supply chain strategy, which illustrates the relevance of various management paradigms. The authors considered four pillars (enablers) as key factors to improve supply chain resilience including: robustness, agility, leanness and flexibility (RALF). Nevertheless, visibility (V) was also incorporated as a resilience sub-criterion suggested by the purchasing manager for this case study.

Since additional criteria such as environmental sustainability and resilience are paramount in designing a successful and competitive supply chain, supplier selection complexity has increased and the necessity for new methodologies is evident. These should be able to tackle this complexity by incorporating three main criteria: traditional business, green and resilience. The vast majority of current literature considers the green and resilient aspects of supplier

selection separately. Realizing the fact that environmental sustainability works towards a system that can sustain its service considering traditional business responsibilities and complying with green development regulations. On the other hand, resilience works to avoid or mitigate an expected or unexpected disruption, or at least mitigate its negative impact towards an ideal goal of environmental sustainability. Hence, resilience and greenness are an ultimate goal of a healthy supply chain management since to obtain a supply chain that could sustain its sustainability, resilience aspect should also be considered simultaneously. Furthermore, the literature support and evident the connections between resilience and environmental sustainability. Derissen et al. (2011) investigated this relationship describing sustainability and resilience as normative and descriptive aspects respectively. Rose (2011) argued that sustainability practices support the improvement after a severe disruption. These practices would not be available without owning deep-rooted resilience linked to disruption recovery. Lebel et al. (2006) presented resilience aspect as a key factor for sustainability, and to cope with green development effectively, resilience management is paramount. Ivanov (2017) analysed the intersections between sustainability and resilience in supply chains aiming to design a resilient supply chain along with uncertainty reduction and sustainability improvement. Giannakis and Papadopoulos (2016) and Ivanov (2017) discuss that the development of environmentally sustainable and resilient supply chains can be improved via the modelling and development of decision support systems from sustainability and resiliency perspectives.

This paper aims to address this need and contributes to the related literature by proposing a unified supplier selection and order allocation approach that considers traditional, green and resilience criteria simultaneously. The evaluation criteria were identified from the literature (e.g., Ha and Krishnan 2008; Govindan et al. 2015; Aissaoui et al. 2007) and in collaboration with the purchasing manager of the real case under study. This includes: traditional (T) criteria (i.e. cost, quality, delivery reliability, operating capacity, turnover, and performance history and lead time); green (G) criteria (i.e., environmental management system, waste management and environmental certificate); resilience (R) criteria (i.e., RALF). The development of this approach can be subsumed into four phases. In phase one, the main traditional, green and resilience criteria and their sub-criteria were identified in a unified framework. AHP was used to integrate judgments from decision makers aiming to determine the weights of the criteria and sub-criteria as a second phase. In the third phase, TOPSIS was applied to evaluate and rank suppliers based on their TGR performance. In the fourth phase, the obtained weights from AHP and TOPSIS were then integrated into a developed multi-objective programming model (MOPM) used to obtain an order allocation plan. This supports decision makers' evaluation regarding suppliers' performance in which the order allocation plan is set considering suppliers' gresilience performance. The MOPM was solved by using the ε-constraint method and TOPSIS was finally used to select the final Pareto solution. The usability of the developed approach was validated within a real case study. The real-world application of the developed approach with a manufacturing company is a practical impact of the current study. This study also contributes to enhancing the supplier selection strategy by incorporating traditional, green and resilience (Gresilience) criteria. The majority of existing literature includes traditional and green supplier selection criteria but not resilience requirements.

The rest of this paper is structured as follows. In the next section, the related literature review is presented as green supplier selection and resilience supplier selection. In Sect. 3, steps followed for applying AHP, TOPSIS are shortly explained. In Sect. 4, the MOPM developed for obtaining a green and resilient supplier selection and order allocation planner is described. In Sect. 5, the developed approach was applied within a real case study. Conclusions, managerial implications and future works are drawn in Sect. 6.

2 Literature review

2.1 Green supplier selection

Previous research studies on traditional criteria are more extensive than the less established green supplier selection (Koberg and Longoni 2018; Brandenburg and Rebs 2015; Govindan et al. 2015). An important work in the area of green supplier selection is Büyüközkan and Çifçi (2012) where they used fuzzy decision-making trial and evaluation laboratory (DEMATEL), fuzzy analytic network process (ANP) and fuzzy TOPSIS in the evaluation of green suppliers for a major manufacturing company, namely Ford Otosan. Recently, Govindan et al. (2015) reviewed published research from 1997 to 2011 on multi-criteria decision making (MCDM) algorithms and mathematical modelling used for green supplier selection problems. Khan et al. (2018) proposed a MCDM approach aimed at evaluating suppliers' sustainable performance. The Fuzzy-Shannon Entropy approach was applied to quantify the sustainability criteria relative importance followed by the application of fuzzy-Inference system to evaluate and rank suppliers. Akman (2015) suggested a two-step supplier-assessment framework to evaluate green suppliers. Kannan et al. (2015) investigated a green supplier selection problem in a plastics manufacturing company using a fuzzy axiomatic design approach. Govindan and Sivakumar (2016) developed an integrated multi-criteria decision-making and multi-objective linear programming approach as an aid to select the best green supplier. Banaeian et al. (2018) compared TOPSIS, visekriterijumska optimizacija i kompromisno resenje (VIKOR) and grey relational analysis (GRA) methods to rank suppliers in the agri-food industry by considering economic and environmental criteria. Hamdan and Cheaitou (2017) applied TOPSIS together with AHP for supplier selection and order allocation based on green criteria. Trapp and Sarkis (2016) proposed a programming model that concurrently considers supplier selection with respect to economic and environmental responsibilities. Song et al. (2017) proposed an integrated approach for evaluating suppliers with respect to economic, green and social criteria using the merit of pairwise comparison method in determining relative importance. The strength of DEMATEL algorithm is in manipulating the complex and intertwined problems with fewer data, and the rough number's advantage in flexibly dealing with vague information. Amorim et al. (2016) proposed an integrated framework to solve supplier selection problems in the processed food industry. As outlined in the literature, different algorithms were used to determine supplier selection and order allocation. However, Chai et al. (2013) and Govindan et al. (2015) show that AHP, VIKOR, TOPSIS and multi-objective programming are the most commonly used techniques.

2.2 Resilient supplier selection

Supply chain management includes a variety of complex activities which may be subjected to unexpected disruptions and resilience is crucial for mitigating them (Wang et al. 2016a, b; Torabi et al. 2015). The reviewed literature suggests that studies using quantitative approaches to solve resilient supplier problem are limited. Mitra et al. (2009) and Sawik (2013) identified several pillars and criteria that should be considered for selecting resilient suppliers. Haldar et al. (2014) developed a fuzzy MCDM approach for supplier selection considering the importance degrees of specific attributes as linguistic variables formulated by triangular and trapezoidal fuzzy numbers. Torabi et al. (2015) proposed a fuzzy stochastic bi-objective optimization model to solve a SS/OA problem to improve the supply chain resilience under operational and disruption risks. Sahu et al. (2016) proposed a supplier evaluation decision

Table 1 Related traditional green/traditional resilient supplier selection studies

References	Aspects			Techniques
	T + R	T + G	T + G + R	
This study			*	AHP + TOPSIS + Multi-objective optimization
Awasthi and Kannan (2016)		*		Fuzzy NGT + VIKOR
Banaeian et al. (2018)		*		TOPSIS + VIKOR + GRA
Büyüközkan and Çifçi (2012)		*		Fuzzy DEMATEL + Fuzzy ANP + Fuzzy TOPSIS
Fallahpour et al. (2016)		*		DEA + Genetic programming
Gencer and Gürpinar (2007)		*		ANP
Hamdan and Cheaitou (2017)		*		AHP + TOPSIS
Hosseini and Barker (2016)	*			Bayesian Network (BN)
Hsu et al. (2013)		*		DEMATEL
Kannan et al. (2014)		*		Fuzzy TOPSIS
Kannan et al. (2015)		*		FAD
Kuo et al. (2010)		*		ANN + MADA + DEA
Lee (2009)	*			Fuzzy AHP
Luthra et al. (2017)		*		AHP and VIKOR
Pramanik et al. (2017)	*			AHP + TOPSIS + QFD
Rajesh and Ravi (2015)	*			AHP + ANP
Sahu et al. (2016)	*			VIKOR
Sawik (2015)	*			Stochastic mixed integer programming
Shaw et al. (2012)		*		Fuzzy AHP and Fuzzy Multi-objective optimization
Pettit et al. (2013)	*			Supply Chain Resilience Assessment and Management (SCRAM™)
Tavana et al. (2017)		*		QFD + ANP
Yazdani et al. (2017)		*		QFD + MCDM

T traditional criteria, *G* green criteria, *R* resilience criteria

support system using VIKOR considering both general and resilience criteria. Pramanik et al. (2016) presented a fuzzy MCDM approach as an aid to developing a resilient supplier selection. Rajesh and Ravi (2015) applied AHP and ANP to supplier selection in resilient supply chains. Klibi and Martel (2012) formulated a mixed integer programming model for handling supplier selection and order allocation problem. Sawik (2013) designed a mixed-integer programming model to solve a supplier selection problem in a supply chain under disruption risks. Table 1 lists further studies conducted to solve the supplier selection problem considering green or resilience aspects.

The literature review highlights a gap in presenting a unified supplier selection and order allocation approach that considers traditional, green and resilience criteria simultaneously. This can support decision makers in coping with green development and unexpected disruptions. This need has inspired the authors to develop a unified traditional business, green and resilient supplier selection and order allocation approach. It is realized from the above-mentioned, analysis in literature review and to the best of our knowledge, the proposed

Table 2 Criteria evaluation scale

Linguistic variable	Scale
Equally important (EI)	1
Weakly important (WI)	3
Strongly more important (SMI)	5
Very strongly important (VSI)	7
Extremely important (EI)	9

study delivers the first study of using the MCDM algorithms to determine the quantitative importance model.

3 Allocation planning: methods

As discussed by Chai et al. (2013) and Govindan et al. (2015) AHP, TOPSIS and multi-objective programming are the most commonly used techniques for the selection of suppliers. This was also supported by Fallahpour and Moghassem (2012) mentioning that AHP and TOPSIS are the popular techniques in tackling evaluation problems. With regards to AHP, the decision makers have the ability to incorporate qualitative and quantitative criteria in the unified evaluation framework. Within the context of this work, AHP and TOPSIS are being used to validate the evaluation outcome obtained via TOPSIS.

3.1 AHP

AHP is a multi-criteria decision making algorithm developed for considering both qualitative and quantitative aspects of decisions (Saaty 1977). It aims to analyse the complex decisions to a series of pairwise comparisons and then reveals the final weight. In this work, AHP was applied to determine the importance weight for each TGR criteria and sub-criteria and Table 2 shows the evaluation scale in terms of linguistic variables that were used to perform pairwise comparisons. Decision makers need to give their opinion regarding the importance of each criteria/sub-criteria with respect to the others. Steps toward the solution of an AHP process can be found in Mathiyazhagan et al. (2015), Bhagwat and Sharma (2007) and Handfield et al. (2002).

3.2 TOPSIS

Hwang and Yoon (1981) developed TOPSIS to select an alternative based on its distance to the ideal solution and the negative ideal solution. In this work, TOPSIS was applied to evaluate and rank suppliers with respect to their TGR performance. The linguistic variables presented in Table 3 were used to evaluate suppliers towards each criterion. Decision makers need to give their opinions about the performance of every supplier based on their TGR performance. In order to find the solution of a decision making problem using TOPIS, we refer to Behzadian et al. (2012), Opricovic and Tzeng (2004) and Wang et al. (2016a, b).

Table 3 Linguistic variables and their equivalent scale used for evaluating suppliers

Linguistic variable	Scale
Very low (VL)	1
Low (L)	3
Medium (M)	5
High (H)	7
Very high (VH)	9

4 Allocation planning: research methodology

A laboratory instrumentation Original Equipment Manufacturer (OEM) plans to develop a resilient supplier selection and order allocation strategy for evaluating its current suppliers in order to react for unexpected events. Additionally, the company is keen to take ownership of its environmental responsibilities. This research supports the company through development of a supplier selection approach to facilitate evaluation and selection of suppliers based on their performance with respect to traditional, green and resilience criteria. Figure 1 shows a hierarchal framework, established for identifying traditional, green and resilience sub-criteria. The three criteria include traditional criteria with sub-criteria of cost, quality, delivery reliability, operating capacity, turnover, performance history and lead time, the green criteria with sub-criteria of environmental management system, waste management and environmental certificate, and the resilience criteria with sub-criteria of visibility, robustness, agility, leanness and flexibility (V-RALF). It is worth mentioning that in addition to the mentioned criteria in the literature, the purchasing manager has suggested additional traditional criteria i.e. lead time and turnover to be included as it will be shown in application Sect. 5. The purchasing manager clarified further in relation to traditional criteria: lead time is very important for the company to be considered because it is related to inventory management and demand forecasting; and turnover represents an indicator for the supplier's capability to cope with the company's demand. AHP was used to determine the importance weight for each criterion and sub-criterion based on linguistic expert's assessment. Next, TOPSIS was adapted towards the evaluation of suppliers based on their performance in TGR criteria shown in Fig. 1. Subsequently, the ranking order of suppliers was determined based on evaluation derived from TOPSIS. Afterwards, a MOPM was developed, incorporating the weights obtained from AHP and TOPSIS to determine the optimal order allocation among suppliers. This integration helps the purchasing team to purchase products from suppliers taking into account their weight (i.e. derived from TOPSIS) with respect to the relative weight of each gresilience criterion (i.e. derived from AHP) based on decision makers' opinion. Figure 2 shows a framework in terms of the processes followed for developing the green and resilient supplier selection and order allocation approach.

4.1 The order allocation planning

This section presents the order allocation planner, which was obtained through the development of a new multi-objective programming model. It was used to support decision makers to order the optimal quantity of products from suppliers considering TGR aspects. Three objective functions were formulated: minimization of related costs (RC), environmental impact and maximization of resilience purchasing.

The MOPM was formulated based on the following sets, parameters and decision variables.

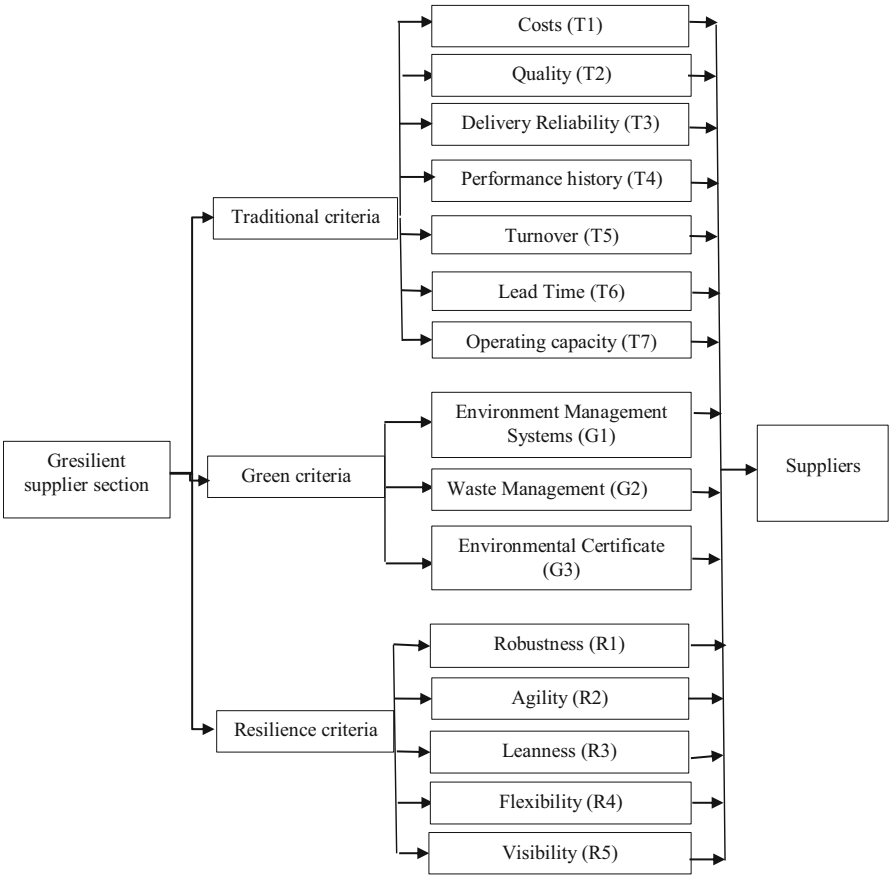

Fig. 1 A hierarchal criteria framework for the gresilient supplier selection and order allocation

C_i^p purchasing cost per unit of product ordered from supplier i
C_i^t fixed unit transportation cost per mile from supplier i
C_i^a fixed administration cost per unit of supplier i
d_i transportation distance (mile) of product from supplier i
TC transportation capacity (units) per lorry
S_i supply capacity (units) of supplier i
D_{min} minimum demand of the manufacturer
D_{max} maximum demand of the manufacturer
CO_{2i} CO_2 emission in gram per mile for each lorry travelling from supplier i
IW^t importance weight of traditional criteria revealed via AHP
IW^g importance weight of green criteria revealed via AHP
IW^r importance weight of resilience criteria revealed via AHP
iw_i^t importance weight of supplier i revealed via TOPSIS towards traditional performance
iw_i^g importance weight of supplier i revealed via TOPSIS towards green performance
iw_i^r importance weight of supplier i revealed via TOPSIS towards resilience performance

Decision variables

q_i quantity of products ordered from supplier i

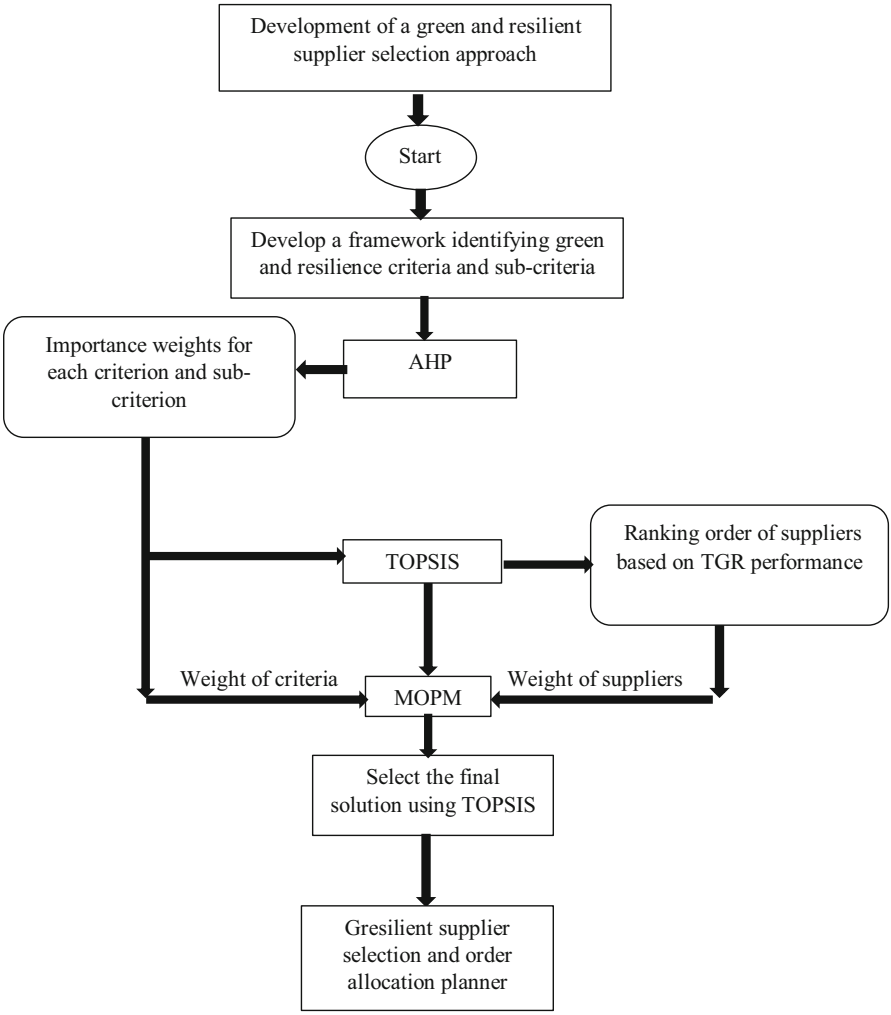

Fig. 2 Schematic representation of the gresilient supplier selection and order allocation approach

Objective function 1 (RC) Equation 1 shows the first objective function that is formulated for minimizing the sum of the purchasing, administration (e.g., ordering) and transportation costs. Furthermore, the importance weight of traditional criteria obtained via AHP and traditional suppliers' weight obtained via TOPSIS were integrated in the first term to reflect the traditional performance of each supplier in the order allocation. The RC function is formulated as follows:

$$Min \quad RC = IW^t \left(\sum_{i \in I} i w_i^t q_i \right) + \sum_{i \in I} C_i^p q_i + \sum_{i \in I} C_i^a q_i + \sum_{i \in I} m C_i^t q_i d_i \tag{1}$$

where m is a multiplicative inverse of the transportation capacity per lorry (TC).

Objective function 2 (EI) Equation 2 shows the second objective function that is formulated for minimizing the EI in terms of CO_2 emissions throughout the transportation process from

suppliers to the company. Furthermore, the weights of green criteria obtained via AHP and the green suppliers' weight obtained via TOPSIS were integrated in the first term to further express the trend towards the supplier with highest green performance. The minimisation of EI can be expressed as follows:

$$Min\ EI = IW^g \left(\sum_{i \in I} i w_i^g q_i \right) + \sum_{i \in I} mCO_{2i} q_i d_i \tag{2}$$

Objective function 3 (Res) Equation 3 shows the third objective function that is formulated for maximizing the resilience value of purchasing. To achieve this aim, suppliers' weights in resilience criteria obtained by TOPSIS were used as a coefficient for suppliers. Also, the overall weight of resilience criteria were multiplied by the formula to further express the trend towards resilience purchasing. The maximisation of Res can be expressed as follows:

$$Max \quad \text{Res} = IW^r \sum_{i \in I} q_i i w_i^r$$

$$\text{Subject to:} \tag{3}$$

Supply capacity constraints

These constraints ensure that the quantity of product ordered from supplier i should not exceed its capacity. It can be formulated as follows:

$$q_i \leq S_i; \quad i = 1, 2, \ldots, I \tag{4}$$

Demand constraints

These constraints ensure that the demands of the company are fulfilled from supplier i. It can be formulated as follows:

$$\sum_{i \in I} q_i \geq D_{\min} \tag{5}$$

$$\sum_{i \in I} q_i \leq D_{\max} \tag{6}$$

Non-negativity constraints

These constraints ensure that the quantity of all products throughout the supply chain are non-negative:

$$q_i \geq 0 \quad \forall i \tag{7}$$

4.1.1 Solution approach: ε-constraint

In this study, the ε-constraint method is used to obtain Pareto solution derived from optimizing the three objective functions (Eqs. 1–3) simultaneously. This method transforms the multi-objective model to a mono-objective model by keeping one of the functions as an objective function (in this study, minimization of expected cost), and treating other functions (in this study, minimization of environmental impact and maximization of resilience purchasing) as constraints limited to ε values (Marler and Arora 2004). Assuming the following multi-objective optimization problem:

$$\max(o_1(x), o_2(x), \ldots, o_i(x)),$$

$$\text{Subject to}$$

$$X \in S; \tag{8}$$

where i denotes the number of objective function o, X is the decision vector and S refers to the feasible solution. In this method, one objective function is optimized, in which others are shifted to the constraint set as follows:

$$\begin{aligned} &\max \quad o_1(x) \\ &\text{Subject to:} \\ &o_1(x) \geq \varepsilon_1 \\ &o_2(x) \geq \varepsilon_2 \\ &o_3(x) \geq \varepsilon_3 \\ &o_i(x) \geq \varepsilon_i \\ &X \in S \end{aligned} \tag{9}$$

It should be noted that here we have a maximization objective; in case we have a minimization objective the shifted objective would need to be less than or equal epsilon value. In this work, the equivalent solution formula is given by:

$$MinRC = IW^t \left(\sum_{i \in I} i w_i^t q_i \right) + \sum_{i \in I} C_i^p q_i + \sum_{i \in I} C_i^a q_i + \sum_{i \in I} m C_i^t q_i d_i \tag{10}$$

Subject to:

$$EI \leq \varepsilon_1 \tag{11}$$

$$Max\,\text{Res} \geq \varepsilon_2 \tag{12}$$

In addition to Eqs. 4–7.

Where every assignment of ε_1 and ε_2 values in Eqs. 11 and 12 would reveal a pareto solutions. For instance, 20 ε values should be assigned to Eqs. 11 and 12 individually to obtain 20 Pareto solutions.

5 Application: a real case study

To validate the applicability and effectiveness of the developed approach, it was applied on a manufacturing company (Company A, henceforth) that assembles measurement equipment in the UK. Company A is an SME that represents one of the world-leading developers and manufacturers of scientific instruments for analysis of organic compounds. Products designed and manufactured by Company A are used in a variety of application areas such as: environmental monitoring, detection of chemical warfare agents, quality control and safety of food products, aroma profiling and environmental forensics. Company A aims to develop a purchasing strategy that supports evaluation of their current suppliers with respect to green and resilience performance in addition to the traditional criteria such as cost and quality. Currently, the main aim of the company is to meet their growth target by 2020. The current and potential turnover has not been revealed upon the company's request. In this respect, the developed approach is applied in this case study to help the purchasing manager to (1) develop a unified TGR purchasing strategy and (2) evaluate their current system resilience in term of the performance of current suppliers.

Three buyers (i.e., B1. B2 and B3) who work in the purchasing department were invited to evaluate the importance of identified criteria illustrated in Fig. 1 using linguistic variables shown in Table 2. B1 has more than 10 years of work experience compared to B2 and B3

has four years of work experience. With regards to weighting the three buyers' opinions, although, the first buyer is the purchasing manager with 10 years of purchasing experience, however, he has joined Company A 4 months ago whereas buyers 2 and 3 have been with the company 4 years. Thus, the purchasing manager has limited knowledge about the company and its suppliers. As a result of changes in the company, it was decided (by the authors and the purchasing manager) to weight their opinions equally (i.e., have the same weight). Two in-depth discussions (each discussion lasted around 2 h) were held with buyers individually to explain, constructively discuss and evaluate the TGR criteria and sub criteria. For the purpose of evaluation, the following definitions were used in discussions with the buyers:

Supply chain resilience "the ability of a [supply chain] to return to its original state or move to a new, more desirable state after being disturbed" Christopher and Peck (2004).
Robustness measures the ability to withstand disruptions to elements within the supply network, either through the immediate availability of alternative suppliers or being capable of quickly planning the incorporation of new suppliers.
Agility evaluates the ability to respond in a quick and well-coordinated manner to comparatively small market opportunities, through having a partner able to handle unexpected/volatile demand.
Leanness assesses the absence of excess/waste and hence the ability to fulfil predictable, base-line, demand in an efficient manner.
Flexibility gauges the ability to respond easily to disturbances in the supply network, whilst maintaining control of costs and lead-times. This involves having processes in place that enable effective response when disturbances in the supply chain are sensed.
Visibility refers to sharing relevant information, which would improve sensing of unexpected orders and fulling them. In other words, it is the ability of suppliers to see the light at the end of tunnel and run towards it based on their flexibility and agility.

5.1 Revealing the weight of TGR criteria: AHP

AHP was implemented as follows to determine the importance weight for each TGR criterion and sub-criterion:

Step 1 Three buyers were invited to perform a pairwise comparison among TGR criteria and sub-criteria (see Fig. 2) using the linguistic variables presented in Table 2.
Step 2 A pair-wise comparison matrix among TGR criteria and sub-criteria was built as shown in Tables 4, 5 and 6.
Step 3 Table 7 shows the importance weights of the traditional criteria, green criteria and resilience criteria as well as their sub-criteria.

According to the calculations shown in Table 7, the weight of traditional criteria (IW^t) is 0. 362 compared to 0.112 and 0.525 for the weight of green criteria (IW^g) and resilience criteria (IW^r) respectively. Subsequently, the resilience criteria obtained the highest weight followed by the traditional criteria, while the green criteria obtained the lowest weight from the perspective of buyers. Thus, resilience criteria are the most important compared to the other criteria of both green and traditional criteria. This complies with the ultimate target of company A in improving their supply chain resilience which represents their current main concern. In the context of traditional criteria, quality has obtained the highest weight of 0.214 compared to the lowest criterion weight for the operating capacity with a weight of 0.079. Also, the resilience criterion of flexibility obtained the highest weight of 0.278. This could be expected as the purchasing manager mentioned during the interview that they have a main

Table 4 Decision matrix among TGR criteria

TGR criteria	T	G	R
B1			
T	1	9	1/5
G		1	1/9
R			1
B2			
T	1	1	1
G		1	1/3
R			1
B3			
T	1	5	1
G		1	1/5
R			1

Table 5 Decision matrix among traditional criteria

Criteria	T1	T2	T3	T4	T5	T6	T7
B1							
T1	1	5	5	7	1	3	1/5
T2		1	5	7	1	7	1
T3			1	7	1	7	1
T4				1	1/9	1/7	1
T5					1	1/7	1/5
T6						1	7
T7							1
B2							
T1	1	5	1	1	5	1	5
T2		1	5	5	4	7	5
T3			1	5	5	1	5
T4				1	1	1	1
T5					1	3	3
T6						1	7
T7							1
B3							
T1	1	1/3	1	1/5	1	1	1
T2		1	1	1/3	1	1	1
T3			1	5	5	1	3
T4				1	5	1	3
T5					1	1/7	1
T6						1	1
T7							1

Table 6 Decision matrix among green and resilience criteria

	Green criteria		
	G1	G2	G3
B1			
G1	1	5	1
G2		1	3
G3			1
B2			
G1	1	5	1
G2		1	1/5
G3			1
B3			
G1	1	5	1
G2		1	5
G3			1

	Resilience criteria				
	R1	R2	R3	R4	R5
B1					
R1	1	1/7	1/7	1/7	1/5
R2		1	7	1/3	1/5
R3			1	1/5	1/5
R4				1	5
R5					1
B2					
R1	1	1	3	1	1/7
R2		1	3	1	1/7
R3			1	1/3	1/7
R4				1	3
R5					1
B3					
R1	1	1	3	1	5
R2		1	5	1	3
R3			1	5	3
R4				1	5
R5					1

issue with some suppliers in having the ability to respond easily to disturbances in the supply network, whilst maintaining control of lead-times.

5.2 Evaluating and ranking suppliers: TOPSIS

In this section, the five suppliers were evaluated and ranked using TOPSIS, based on their TGR performance. After determining the importance for each TGR criterion, TOPSIS was implemented to obtain the ranking order of suppliers, based on their TGR performance.

Table 7 Weights of TGR criteria and sub-criteria obtained by AHP

Criteria	Weight	Ranking	Sub-criteria	Weight	Ranking
Traditional	0.362	2	T1	0.191	2
			T2	0.214	1
			T3	0.167	3
			T4	0.115	5
			T5	0.088	6
			T6	0.143	4
			T7	0.079	7
Green	0.112	3	G1	0.434	1
			G2	0.265	2
			G3	0.300	3
Resilience	0.525	1	R1	0.126	5
			R2	0.187	3
			R3	0.159	4
			R4	0.278	1
			R5	0.248	2

CR = 0.0854

Step 1 The buyers were again invited to evaluate the performance of five suppliers (S1–S5), that were selected by the purchasing manager, with respect to each sub-criterion using the scale previously presented in Table 3. However, the third buyer evaluated the first supplier only, clarifying that he does not work with the others. Table 8 presents the evaluation of five suppliers based on three buyers' opinions. In this context, weights of their opinions were considered equally for the reason mentioned previously.
Step 2 Table 9 shows matrix of normalized numbers and weighted normalized numbers which was obtained by multiplying the sub-criteria weights obtained by the AHP with the normalized matrix.
Step 3 he distance of each supplier from the positive ideal solution (d_i^+) and the negative ideal solution (d_i^-) are calculated. The closeness coefficient (CC) for each supplier is determined based the obtained distances. The results are reported in Table 10.

5.3 The order allocation planner: MOPM

After quantifying the suppliers' performance towards TGR criteria, decision makers in Company A need to know who to order the metal sheet from and what the optimal order quantity from each supplier is. This is based on their performance and consideration of the three objectives (i.e., minimization of expected cost, environmental impact and maximization of resilience purchasing). Thus, to support them in ordering the right quantity from the right supplier, the MOPM developed in Sect. 4 was applied as follows:

Step 1 Table 11 presents collected data related to each supplier from the purchasing manager. However, data related to TGR weights and TGR suppliers' weights were taken from AHP and TOPSIS, respectively.
Step 2 The ε-constraint presented in Sect. 4.1.1 was implemented to solve the three objectives optimization problem in terms of obtaining Pareto solutions. In this work, the expected cost minimization was kept as an objective function. Minimization of environmental impact and maximization of V-RALF are moved to ε-based constraints.

Table 8 Evaluation of suppliers based on their TGR performance

Criteria	Sub-criteria	Sl	S2	S3	S4	S5
B1						
Traditional	T1	H	H	M	M	M
	T2	M	M	M	M	M
	T3	M	M	M	M	M
	T4	VL	L	M	M	M
	T5	H	L	M	L	L
	T6	M	M	M	M	M
	T7	H	M	M	M	M
Green	G1	M	M	M	M	M
	G2	M	M	M	M	M
	G3	M	M	M	M	M
Resilience	R1	M	M	M	H	L
	R2	H	H	M	M	L
	R3	M	M	M	L	L
	R4	H	M	L	H	L
	R5	L	L	L	M	L
B2						
Traditional	T1	H	M	M	H	M
	T2	M	H	M	M	VH
	T3	L	H	M	M	VH
	T4	M	H	M	H	VH
	T5	H	M	M	M	H
	T6	M	M	M	M	M
	T7	L	L	H	H	M
Green	G1	M	H	H	M	H
	G2	H	H	H	M	M
	G3	M	H	H	M	H
Resilience	R1	VL	L	M	L	L
	R2	H	L	M	M	L
	R3	M	H	H	H	H
	R4	H	L	M	L	L
	R5	L	M	M	H	H
B3						
Traditional	T1	L	–	–	–	–
	T2	M	–	–	–	–
	T3	M	–	–	–	–
	T4	M	–	–	–	–
	T5	M	–	–	–	–
	T6	M	–	–	–	–
	T7	M	–	–	–	–
Green	G1	L	–	–	–	–
	G2	M	–	–	–	–
	G3	M	–	–	–	–

Table 8 continued

Criteria	Sub-criteria	Sl	S2	S3	S4	S5
Resilience	R1	L	–	–	–	–
	R2	VL	–	–	–	–
	R3	H	–	–	–	–
	R4	M	–	–	–	–
	R5	M	–	–	–	–

Step 2.1 Objective functions two and three were solved individually to obtain the upper and lower values for each objective. The values between upper and lower for the two objectives were divided into segments. The segment values were assigned individually to ε1 and ε2.
Step 3 Fig. 3 depicts Pareto frontiers among the three objective functions output that were developed based on 130 solutions. For the sake of simplicity, Table 12 shows selected 18 Pareto solutions associated with the selected suppliers and the order allocation plan for the 18 solutions. For instance, solution 2 required minimum costs of 387514.47, reveals minimum CO_2 emissions of 2037586.82 and leads to maximum resilience value of purchasing 3240.07. Also, this solution is associated with a selection of suppliers 2, 3, 4 and 5 (0 1 1 1 1) in which 1853 units should be ordered from supplier 1483 units from supplier 3, 3000 units should be ordered from supplier 4 and 2500 units should be ordered from supplier 5. It is worthy to mention that more Pareto solutions can be obtained by varying epsilon values within the defined range.
Step 4 Each of these solutions is associated with a different order allocation plan as shown in Table 12. Thus, the purchasing manager has asked to select one solution to get the final order allocation. However, selecting a solution out of 18 was a challenge decision. Thus, TOPSIS was applied again to help the purchasing manager in selecting the final solution that is closest to the ideal solution and furthest from the worst solution. Accordingly, solution number 9 was selected as the final solution to get the optimal order allocation as it showed the highest closeness coefficient ($CC = 0.5821$). Based on this solution, the minimum total cost is 431520.03; the minimum CO_2 emissions is 3167654.78 and the maximum value of resilience pillars (V-RALF) is 3572.44. Also, this solution is obtained via an allocation of $\varepsilon_1 = 3167737.23$ and $\varepsilon_2 = 3572.27$. Based on the selected solution, the optimal order allocation plan is illustrated in Fig. 4. As shown in this figure, the buyers should order 3332 units from supplier 1, 1146 units from supplier 3, 3000 units from supplier 4 and 2500 units from supplier 5. It is noticed that all solutions lead to select less than 5 suppliers. It is noteworthy that this complies with the long-term purchasing strategy to reduce the administration costs by having less than 5 suppliers (current scenario). The purchasing manager commented that this will provide more time to buyers seeking and evaluating new suppliers. This also complies with the purchasing manager's short-term plan (to be achieved by 2018) to have an average of 3 suppliers to satisfy all demands rather than five.

The developed MOPM was coded in Python and solved using GUROBI solver. The computational (run) time is neglected as it was in a few seconds since we have small-sized case study.

Table 9 Normalized and weighted normalized decision matrices

	T1	T2	T3	T4	T5	T6	T7	G1	G2	G3	R1	R2	R3	R4	R5
Normalized															
S1	0.227	0.192	0.171	0.155	0.284	0.217	0.208	0.230	0.192	0.165	0.162	0.284	0.227	0.271	0.208
S2	0.243	0.231	0.237	0.211	0.179	0.217	0.208	0.162	0.231	0.228	0.265	0.224	0.182	0.257	0.170
S3	0.203	0.192	0.197	0.211	0.224	0.217	0.250	0.243	0.231	0.228	0.221	0.224	0.273	0.171	0.226
S4	0.122	0.115	0.118	0.127	0.090	0.130	0.125	0.122	0.154	0.152	0.221	0.134	0.091	0.171	0.170
S5	0.203	0.269	0.276	0.296	0.224	0.217	0.208	0.243	0.192	0.228	0.132	0.134	0.227	0.129	0.226
Weighted normalized															
S1	0.044	0.041	0.029	0.018	0.025	0.031	0.017	0.100	0.051	0.049	0.020	0.053	0.036	0.076	0.052
S2	0.047	0.050	0.040	0.024	0.016	0.031	0.017	0.070	0.061	0.068	0.033	0.042	0.029	0.072	0.042
S3	0.039	0.041	0.033	0.024	0.020	0.031	0.020	0.106	0.061	0.068	0.028	0.042	0.043	0.048	0.056
S4	0.023	0.025	0.020	0.015	0.008	0.019	0.010	0.053	0.041	0.046	0.028	0.025	0.014	0.048	0.042
S5	0.039	0.058	0.046	0.034	0.020	0.031	0.017	0.106	0.051	0.068	0.017	0.025	0.036	0.036	0.056

Table 10 Closeness coefficient and distances from the positive ideal/negative ideal solutions related to suppliers

	d_i^+	d_i^-	CC	Rank
S1	3.321	0.237	0.666	3
S2	3.320	0.232	0.653	5
S3	3.316	0.232	0.654	4
S4	3.378	0.285	0.778	1
S5	3.321	0.238	0.670	2

Table 11 Date of the current case study related to the implementation of the MOPM

Variable	S1	S2	S3	S4	S5
C_i^p (£/unit)	40	45	42	39	40
C_i^t (£/mile)	1.5	1.5	1.5	1.5	1.5
C_i^a (£/unit)	1.2	1.2	1.2	1.2	1.2
d_i (mile)	150	13	122	82	133
TC (units)	100	100	100	100	100
m	0.01	0.01	0.01	0.01	0.01
S_i (units)	9500	7000	4000	3000	2500
D_{min} (units)			8820		
D_{max} (units)			10600		
CO_{2i} (g/mile)	260	260	260	260	260
IW^t	0.363	0.363	0.363	0.363	0.363
IW^g	0.112	0.112	0.112	0.112	0.112
IW^r	0.525	0.525	0.525	0.525	0.525
iw_i^t	0.758	0.738	0.751	0.863	0.713
iw_i^g	0.471	0.390	0.342	0.597	0.391
iw_i^r	0.610	0.641	0.630	0.744	0.727

5.4 Sensitivity analysis

Sensitivity analysis is conducted to investigate how the changes of input data may affect the results of the decision-making model. In this study, a sensitivity analysis is performed to study the effects of changing the weight of TGR criteria on the ranking of suppliers. Eight different scenarios of weights (see Table 13) are assigned to TGR criteria in Eq. 10. Table 14 shows the closeness coefficient (CC) for each supplier related to each scenario. As shown in Table 14, the analysis shows that the evaluation and ranking process is slightly sensitive to variation in the TRG criteria weight. For instance, in scenario 6, the ranking order has been changed to S4>S1>S2>S3>S5 compared to the original order of S4>S5>S1>S3>S2. This could be related to the resilience criteria as S1 has reasonable traditional and green performance but an average of medium resilience performance which made it as the third suppliers in the original evaluation since the resilience criteria revealed highest weight based on decision makers' evaluation. However, once an almost equal weight allocated for the TGR criteria as in the sensitivity analysis, S1 revealed a high overall performance putting it as the second-best supplier. Generally, suppliers 4 and 1 are always ranked first and second in all scenarios respectively.

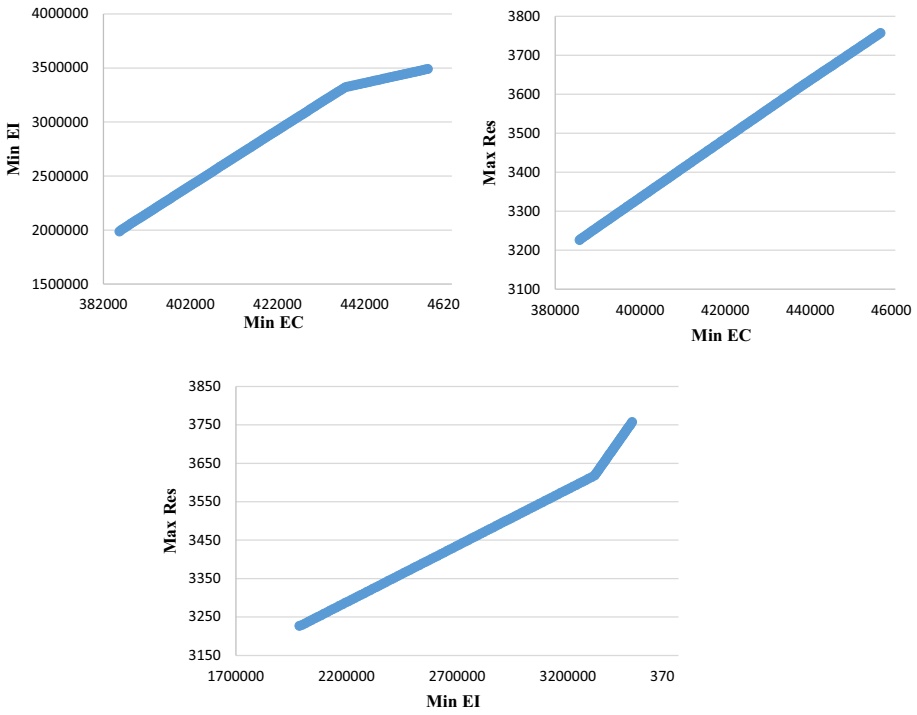

Fig. 3 Pareto frontiers

5.5 Managerial implications

This research delivers the purchasing team a user-friendly decision support system that can be used as a tool for improving their supplier selection process. Specifically, it allows for a more consistent approach to the application of multiple (Traditional, Green and Resilience) criteria. As has been identified in supply chain literature a critical part of the supplier selection process is determining the relative importance of the decision-making factors. This decision support tool addresses some of the challenges associated with the trade-offs that need to be made during supplier selection. Furthermore, through the use of these techniques a manager or buyer is able to express their perception of a supplier and enter it into the tool.

Taking a broader perspective, this collaborative research provides the purchasing manager and their team with an advanced and modern thoughtful regarding their required purchasing strategy. This helps them to contribute towards the development of a resilient business that the company aims to achieve in 2020, in addition to green development that would advance the company's industry profile. This work had allowed them to appreciate the benefits of a gresilient approach. Furthermore, this collaboration cultured the purchasing department about the crucial necessity for including gresilience criteria as an alternative to the traditional criteria only.

Furthermore, this decision support tool could be used by purchasing or supply chain managers to perform benchmarking of suppliers. This is of particular importance when a company wishes to pursue a multi-sourcing policy where the company would like to have multiple suppliers to enhance their overall resilience for certain component types.

Table 12 Selected Pareto solutions

#	ε values		Objective function solutions							
	ε_1	ε_2	Min EC	Min EI	Max Res	Selected supplier				
1	1967024.50	3219.21	385897.36	1966924.61	3227.25	1	1	0	1	1
2	2037654.66	3239.98	387514.47	2037586.82	3240.07	0	1	1	1	1
3	2108284.82	3260.74	390264.82	2108191.42	3260.88	0	1	1	1	1
4	2532065.78	3385.36	406726.97	2531915.09	3385.44	0	1	1	1	1
5	2602695.95	3406.12	409479.11	2602657.45	3406.27	0	1	1	1	1
6	2673326.11	3426.89	412229.46	2673262.06	3427.08	0	1	1	1	1
7	3026476.91	3530.74	426020.99	3026292.24	3531.04	1	0	1	1	1
8	3097107.07	3551.50	428770.62	3097078.80	3551.74	1	0	1	1	1
9	3167737.23	3572.27	431520.03	3167654.78	3572.44	1	0	1	1	1
10	3520888.03	3676.12	445537.83	3392655.44	3676.32	1	0	0	1	1
11	3591518.19	3696.88	448379.96	3418008.87	3697.13	1	0	0	1	1
12	3662148.35	3717.65	451222.10	3443362.30	3717.95	1	0	0	1	1
13	3732778.51	3738.42	454020.50	3468325.68	3738.45	1	0	0	1	1
14	3803408.67	3759.19	456862.64	3493679.11	3759.26	1	0	0	1	1
15	3874038.83	3779.96	459973.39	3350089.02	3779.97	1	0	1	1	1
16	3944668.99	3800.73	463093.60	3206062.04	3800.74	1	0	1	1	1
17	4015299.15	3821.50	466953.54	2696099.91	3821.50	0	1	1	1	1
18	4085929.31	3842.26	471845.11	1677012.84	3842.27	0	1	0	1	1

#	Order allocation				
	S1	S2	S3	S4	S5
1	983	2337	0	3000	2500
2	0	1853	1483	3000	2500
3	0	1678	1723	3000	2500
4	0	625	3171	3000	2500
5	0	449	3414	3000	2500
6	0	274	3654	3000	2500
7	2109	0	2204	3000	2500
8	2720	0	1676	3000	2500
9	3332	0	1146	3000	2500
10	4841	0	0	3000	2500
11	4906	0	0	3000	2500
12	4971	0	0	3000	2500
13	5035	0	0	3000	2500
14	5100	0	0	3000	2500
15	3128	0	1972	3000	2500
16	1150	0	3950	3000	2500
17	0	1504	3596	3000	2500
18	0	5100	0	3000	2500

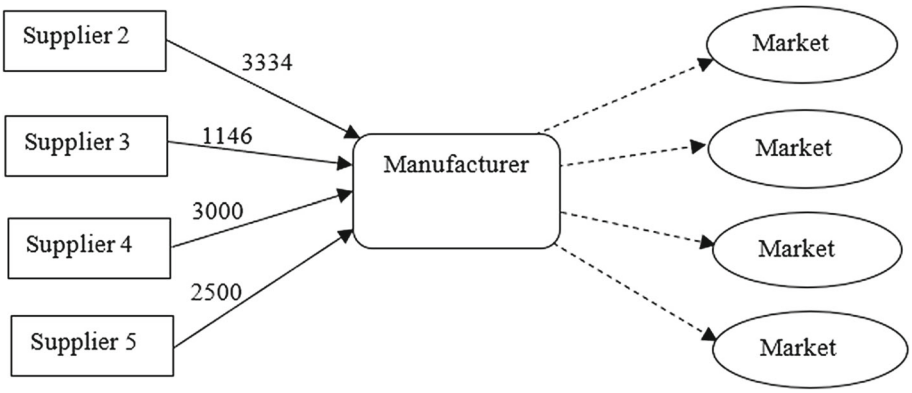

Fig. 4 The optimal order allocation for the case under study

With regards to suppliers, this work may also help them (i.e., suppliers 1 and 2) to enhance their performance according to the highlighted criteria. This is because the presented decision support tool allows the purchasing manager to deliver feedback in an appropriately timed manner to specific suppliers. Therefore, the supplier can evaluate its current performance with its historical performance and make essential adjustments to improve performance.

6 Conclusions

Traditional supplier selection criteria include elements such as cost and product quality but over the last decade companies have been challenged to 'go green' and take responsibility for their environmental impact. This is admirable but not necessarily sufficient to guarantee sustainable operations, due to the risk of unexpected supply chain disturbances (Norrman and Jansson 2004; Tang 2006). During or following a disruption, supply chain performance is normally compromised. Thus, companies and supply chains must be resilient in efficiently reacting to unexpected events. It is generally accepted that the overall performance of a supply chain is enhanced through effective supplier selection. Therefore, to cope with the multiple demands on a supply chain business, a supplier selection approach that considers traditional, green and resilience criteria is of paramount importance.

This work presents a development of a unified green and resilient (Gresilient) supplier selection and order allocation approach considering traditional, green and resilience criteria. A supplier selection framework was developed by identifying traditional, green and resilience criteria and sub-criteria. Five steps were followed to evaluate and rank suppliers and allocate the optimal allocation in quantity of orders. Firstly, AHP was applied to evaluate the importance of each criterion and sub-criterion based on the linguistic evaluation of decision makers. The AHP results showed that resilience criteria play a current trend for the company over two the other two criteria (traditional and green criteria). Secondly, TOPSIS was applied to reveal the ranking order of suppliers based on their TGR performance with respect to the importance weight of each criterion and sub-criterion revealed via AHP. Generally, all suppliers revealed low resilience performance, which does not comply with the company's strategy. Thirdly, a MOPM was developed to obtain the optimal order allocation among suppliers considering their TGR performance as the weights revealed via AHP and TOPSIS were integrated in the MOPM. The ε-constraint method was then used to obtain Pareto solutions and TOPSIS was

Table 13 Eight different scenarios of TGR criteria weights allocated for TOPSIS individually

	T1	T2	T3	T4	T5	T6	T7	G1	G2	G3	R1	R2	R3	R4	R5
r1	0.124	0.110	0.181	0.129	0.105	0.122	0.165	0.162	0.182	0.150	0.190	0.125	0.192	0.108	0.157
r2	0.110	0.144	0.126	0.166	0.137	0.103	0.134	0.110	0.109	0.152	0.118	0.182	0.110	0.108	0.123
r3	0.134	0.131	0.142	0.118	0.182	0.164	0.157	0.104	0.175	0.112	0.156	0.112	0.114	0.190	0.194
r4	0.197	0.105	0.130	0.152	0.144	0.119	0.161	0.177	0.169	0.156	0.124	0.104	0.125	0.148	0.193
r5	0.171	0.190	0.172	0.191	0.150	0.121	0.195	0.103	0.134	0.103	0.140	0.130	0.145	0.165	0.175
r6	0.172	0.199	0.110	0.157	0.136	0.173	0.108	0.108	0.151	0.195	0.136	0.159	0.128	0.166	0.142
r7	0.187	0.177	0.135	0.161	0.161	0.186	0.153	0.129	0.123	0.144	0.160	0.163	0.132	0.107	0.122
r8	0.113	0.140	0.131	0.139	0.170	0.140	0.150	0.105	0.139	0.151	0.183	0.139	0.188	0.123	0.161

Table 14 Ranking order of suppliers revealed via the sensitivity analysis

	CC1	*CC2*	*CC3*	*CC4*	*CC5*	Rank
r1	0.467	0.480	0.489	0.544	0.487	S4>S1>S3>S2>S5
r2	0.525	0.470	0.473	0.547	0.433	S4>S1>S3>S2>S5
r3	0.522	0.400	0.425	0.551	0.433	S4>S1>S5>S3>S2
r4	0.474	0.439	0.437	0.585	0.488	S4>S1>S5>S3>S2
r5	0.478	0.444	0.429	0.573	0.484	S4>S1>S5>S3>S2
r6	0.521	0.462	0.456	0.539	0.440	S4>S1>S2>S3>S5
r7	0.514	0.458	0.464	0.524	0.457	S4>S1>S3>S2>S5
r8	0.503	0.439	0.479	0.535	0.438	S4>S1>S3>S2>S5

applied again to select the final Pareto solution as the fourth and fifth steps respectively. The results demonstrate the applicability of the developed approach in helping the purchasing manager at company A to identify a traditional, green and resilient purchasing strategy and evaluate their suppliers. Additionally, it guides the company to order the right quantity of material from the right suppliers according to their performance. The developed evaluation approach was delivered to the purchasing manager as an Excel worksheet to be used for their upcoming supplier assessments, it was a much-appreciated tool to simplify and support their decisions.

Companies that function under similar conditions could use the developed approach for evaluating the healthiness of their suppliers in terms of resilience and greenness. Also, it can be used by suppliers themselves to improve their service through the evaluation of their status with respect to the defined traditional, green and resilience criteria and sub-criteria. This work has established a foundation for future research avenues in highlighting the need for considering resilience pillars in green purchasing strategy.

The study has been focused on chemical manufacturing industry. Similar study conducted in different sector such food industry may need some bit different criteria such as freshness and safety of food products. This would also further prove the applicability of the developed approach in solving similar supplier selection and order allocation problems. Also, this study is limited in considering equal weight for buyers' opinions. Thus, it was suggested to the purchasing manager to consider different weights considering seniority of buyers into the upcoming evaluation. In the context of the SME case study, the number of decision makers is limited by 3 (the purchasing manager and two buyers) as this was the purchasing team that was available and presented to the research team to validate the developed approach. However, the Excel-based evaluation tool was developed to accommodate 8 decision makers. The purchasing manager was told that all buyers can input their evaluation in the upcoming evaluation of criteria/or suppliers. Thus, it would be interesting to have more decision makers that further illustrate the applicability of the developed approach in aggregating opinions of multiple decision makers. Furthermore, the size of input data (e.g., demand and supply capacity) used in the MOPM reflects the context of case study. Therefore, the capability of the developed MOPM in handling large-sized problem within a reasonable running time has not been explored.

The ongoing work includes the incorporation of social criteria to supplier evaluation. As future research, the developed multi-objective model can be re-developed as a fuzzy multi-objective model to cope with the dynamic nature of some input parameters such as purchasing cost, demands and capacity of suppliers. It would also be interesting to answer the question—how about incorporating the company's internal resilience criteria (pillars)

(e.g., redundancy management, ordering management and operation management) into the evaluation approach and how this could improve their purchasing strategy?

Acknowledgements The authors acknowledge the financial support from the European Regional Development Fund through the Welsh Government for ASTUTE 2020 (Advanced Sustainable Manufacturing Technologies) to facilitate this work. Also, the first author would like to express his gratitude to the Research Council (TRC) in the Sultanate of Oman for their support of this work.

References

Aissaoui, N., Haouari, M., & Hassini, E. (2007). Supplier selection and order lot sizing modeling: A review. *Computers & Operations Research, 34*(12), 3516–3540.

Akman, G. (2015). Evaluating suppliers to include green supplier development programs via fuzzy c-means and VIKOR methods. *Computers & Industrial Engineering, 86,* 69–82.

Alikhani, R., Torabi, S. A., & Altay, N. (2018). Strategic supplier selection under sustainability and risk criteria. *International Journal of Production Economics*, *208*, 69–82.

Amorim, P., et al. (2016). Supplier selection in the processed food industry under uncertainty. *European Journal of Operational Research, 252*(3), 801–814.

Awasthi, A., & Kannan, G. (2016). Green supplier development program selection using NGT and VIKOR under fuzzy environment. *Computers & Industrial Engineering, 91,* 100–108.

Banaeian, N., Mobli, H., Fahimnia, B., Nielsen, I. E., & Omid, M. (2018). Green supplier selection using fuzzy group decision making methods: A case study from the agri-food industry. *Computers & Operations Research, 89,* 337–347.

BBC News. (2011). *Japan disaster: Supply shortages in three months*. BBC News. Retrieved date 11.02.17.

Behzadian, M., Otaghsara, S. K., Yazdani, M., & Ignatius, J. (2012). A state-of the-art survey of TOPSIS applications. *Expert Systems with Applications, 39*(17), 13051–13069.

Bhagwat, R., & Sharma, M. K. (2007). Performance measurement of supply chain management using the analytical hierarchy process. *Production Planning and Control, 18*(8), 666–680.

Brandenburg, M., & Rebs, T. (2015). Sustainable supply chain management: A modeling perspective. *Annals of Operations Research, 229*(1), 213–252.

Burinskiene, A., Lorenc, A., & Lerher, T. (2018). A simulation study for the sustainability and reduction of waste in warehouse logistics. *International Journal of Simulation Modelling (IJSIMM), 17*(3), 485–497.

Büyüközkan, G., & Çifçi, G. (2012). A novel hybrid MCDM approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS to evaluate green suppliers. *Expert Systems with Applications, 39*(3), 3000–3011.

Chai, J., Liu, J. N. K., & Ngai, E. W. T. (2013). Application of decision-making techniques in supplier selection: A systematic review of literature. *Expert Systems with Applications, 40*(10), 3872–3885.

Chang, K. H. (2017). A novel supplier selection method that integrates the intuitionistic fuzzy weighted averaging method and a soft set with imprecise data. *Annals of Operations Research*, *272*(1–2), 139–157.

Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *The International Journal of Logistics Management, 15*(2), 1–14.

Derissen, S., Quaas, M. F., & Baumgärtner, S. (2011). The relationship between resilience and sustainability of ecological-economic systems. *Ecological Economics, 70*(6), 1121–1128.

Dickson, G. (1966). An analysis of vendor selection systems and decisions. *Journal of Purchasing, 2*(1), 5–17.

Fallahpour, A. R., & Moghassem, A. R. (2012). Evaluating applicability of VIKOR method of multicriteria decision making for parameters selection problem in rotor spinning. *Fiber Polym, 13*(6), 802–808.

Fallahpour, A., Olugu, E. U., Musa, S. N., Khezrimotlagh, D., & Wong, K. Y. (2016). An integrated model for green supplier selection under fuzzy environment: Application of data envelopment analysis and genetic programming approach. *Neural Computing and Applications, 27*(3), 707–725.

Figueira, J., Greco, S., & Ehrgott, M. (2005). *Multiple criteria decision analysis: State of the art surveys*. New York: Springer.

Gencer, C., & Gürpinar, D. (2007). Analytic network process in supplier selection: A case study in an electronic firm. *Applied Mathematical Modelling, 31*(11), 2475–2486.

Giannakis, M., & Papadopoulos, T. (2016). Supply chain sustainability: A risk management approach. *International Journal of Production Economics, 171*(4), 455–470.

Govindan, K., Kadziński, M., & Sivakumar, R. (2017). Application of a novel PROMETHEE-based method for construction of a group compromise ranking to prioritization of green suppliers in food supply chain. *Omega, 71,* 129–145.

Govindan, K., Rajendran, S., Sarkis, J., & Murugesan, P. (2015). Multi criteria decision making approaches for green supplier evaluation and selection: A literature review. *Journal of Cleaner Production, 98,* 66–83.
Govindan, K., & Sivakumar, R. (2016). Green supplier selection and order allocation in a low-carbon paper industry: Integrated multi-criteria heterogeneous decision making and multi-objective linear programming approaches. *Annals of Operations Research, 238*(1–2), 243–276.
Ha, S. H., & Krishnan, R. (2008). A hybrid approach to supplier selection for the maintenance of a competitive supply chain. *Expert Systems with Applications, 34*(2), 1303–1311.
Haldar, A., Ray, A., Banerjee, D., & Ghosh, S. (2014). Resilient supplier selection under a fuzzy environment. *International Journal of Management Science and Engineering Management, 9*(2), 147–156.
Hall, J. (2010). *Volcanic ash cloud leaves shops facing shortages of fruit, vegetables and medicine*. London: The Daily Telegraph.
Hamdan, S., & Cheaitou, A. (2017). Supplier selection and order allocation with green criteria: An MCDM and multi-objective optimization approach. *Computers & Operations Research, 81,* 282–304.
Handfield, R., Walton, S. V., Sroufe, R., & Melnyk, S. A. (2002). Applying environmental criteria to supplier assessment: A study in the application of the analytical hierarchy process. *European Journal of Operational Research, 141*(1), 70–87.
Hosseini, S. M., & Barker, K. (2016). A Bayesian network model for resilience-based supplier selection. *International Journal of Production Economics, 180,* 68–87.
Hsu, C. W., Kuo, T. C., Chen, S. H., & Hu, A. H. (2013). Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. *Journal of Cleaner Production, 56,* 164–172.
Hwang, C. L., & Yoon, K. (1981). *Multiple attribute decision making: Methods and applications*. New York: Springer.
Ivanov, D. (2017). Revealing interfaces of supply chain resilience and sustainability: A simulation study. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2017.1343507.
Jamshidi, M., Darwesh, A. M., Lorenc, A., Ranjbari, M., & Meybodi, M. R. (2018). A precise algorithm for detecting malicious Sybil nodes in mobile wireless sensor networks. *IEIE Transactions on Smart Processing & Computing, 7*(6), 457–466.
Kannan, D., de Sousa Jabbour, A. B. L., & Jabbour, C. J. C. (2014). Selecting green suppliers based on GSCM practices: Using fuzzy TOPSIS applied to a Brazilian electronics company. *European Journal of Operational Research, 233*(2), 432–447.
Kannan, D., Govindan, K., & Rajendran, S. (2015). Fuzzy axiomatic design approach based green supplier selection: A case study from Singapore. *Journal of Cleaner Production, 96,* 194–208.
Kannan, D., Khodaverdi, R., Olfat, L., Jafarian, A., & Diabat, A. (2013). Integrated fuzzy multi criteria decision making method and multi-objective programming approach for supplier selection and order allocation in a green supply chain. *Journal of Cleaner Production, 47,* 355–367.
Kaur, H., & Singh, S. P. (2016). Sustainable procurement and logistics for disaster resilient supply chain. *Annals of Operations Research*, *283*(1), 309–354.
Khan, S. A., Kusi-Sarpong, S., Arhin, F. K., & Kusi-Sarpong, H. (2018). Supplier sustainability performance evaluation and selection: A framework and methodology. *Journal of Cleaner Production, 205,* 964–979.
Klibi, W., & Martel, A. (2012). Scenario-based supply chain network risk modeling. *European Journal of Operational Research, 223*(3), 644–658.
Koberg, E., & Longoni, A. (2018). A systematic review of sustainable supply chain management in global supply chains. *Journal of Cleaner Production*, *207*, 1084–1098.
Kuo, R. J., Wang, Y. C., & Tien, F. C. (2010). Integration of artificial neural network and MADA methods for green supplier selection. *Journal of Cleaner Production, 18*(12), 1161–1170.
Lebel, L., Anderies, J. M., Campbell, B., Folke, C., Hatfield-Dodds, S., Hughes, T. P., et al. (2006). Governance and the capacity to manage resilience in regional social–ecological systems. *Ecology and Society, 11*(1), 1–21.
Lee, A. H. (2009). A fuzzy supplier selection model with the consideration of benefits, opportunities, costs and risks. *Expert Systems with Applications, 36*(2/2), 2879–2893.
Lorenc, A., & Lerher, T. (2019). Effectiveness of product storage policy according to classification criteria and warehouse size. *FME Transactions, 47*(1), 142–150.
Luthra, S., Govindan, K., Kannan, D., Mangla, S. K., & Garg, C. P. (2017). An integrated framework for sustainable supplier selection and evaluation in supply chains. *Journal of Cleaner Production, 140*(3), 1686–1698.
Marler, R. T., & Arora, J. S. (2004). Survey of multi-objective optimization methods for engineering. *Structural and Multidisciplinary Optimization*, *26*(6), 369–395.

Mathiyazhagan, K., Diabat, A., Al-Refaie, A., & Xu, L. (2015). Application of analytical hierarchy process to evaluate pressures to implement green supply chain management. *Journal of Cleaner Production, 107,* 229–236.

Mitra, K., Gudi, R. D., Patwardhan, S. C., & Sardar, G. (2009). Towards resilient supply chains: Uncertainty analysis using fuzzy mathematical programming. *Chemical Engineering Research and Design, 87*(7), 967–981.

Mohammed, A. (2020). Towards 'gresilient' supply chain management: A quantitative study. *Resources, Conservation and Recycling*, *155*, 104641.

Mohammed, A., Harris, I., & Dukyil, A. (2019a). A trasilient decision making tool for vendor selection: A hybrid-MCDM algorithm. *Management Decision, 57*(2), 372–395.

Mohammed, A., Harris, I., & Govindan, K. (2019b). A hybrid MCDM–FMOO approach for sustainable supplier selection and order allocation. *International Journal of Production Economics*, *217*, 171–184.

Mohammed, A., Harris, I., Soroka, A., & Nujoom, R. (2018a). A hybrid MCDM-fuzzy multi-objective programming approach for a G-resilient supply chain network design. *Computers & Industrial Engineering*, *127*, 297–312.

Mohammed, A., Harris, I., Soroka, A., Naim, M. M., & Ramjaun, T. (2018b). Evaluating green and resilient supplier performance: AHP-fuzzy topsis decision-making approach. In *ICORES* (pp. 209–216).

Mohammed, A., & Wang, Q. (2017). The fuzzy multi-objective distribution planner for a green meat supply chain. *International Journal of Production Economics, 184,* 47–58.

Norrman, A., & Jansson, U. (2004). Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident. *International Journal of Physical Distribution and Logistics Management, 34*(5), 434–456.

Nujoom, R., Mohammed, A., & Wang, Q. (2019). Drafting a cost-effective approach towards a sustainable manufacturing system design. *Computers & Industrial Engineering, 133,* 317–330.

Nujoom, R., Wang, Q., & Mohammed, A. (2018). Optimisation of a sustainable manufacturing system design using the multi-objective approach. *The International Journal of Advanced Manufacturing Technology, 96*(5–8), 2539–2558.

Opricovic, S., & Tzeng, G. H. (2004). Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research, 156*(2), 445–455.

Ortega, F., & Taşpınar, S. (2018). Rising sea levels and sinking property values: Hurricane Sandy and New York's housing market. *Journal of Urban Economics*, *106*, 81–100.

Pettit, T. J., Croxton, K. L., & Fiksel, J. (2013). Ensuring supply chain resilience: Development and implementation of an assessment tool. *Journal of Business Logistics, 34*(1), 46–76.

Pramanik, D., Subhash, N., Haldar, A., Mondal, S. C., Naskar, S. N., & Ray, A. (2017). Resilient supplier selection using AHP–TOPSIS–QFD under a fuzzy environment. *International Journal of Management Science and Engineering Management, 12*(1), 45–54.

Purvis, L., Spall, S., Naim, M., & Spiegler, V. (2016). Developing a resilient supply chain strategy during 'boom' and 'bust'. *Production Planning & Control, 27*(7–8), 579–590.

Rajesh, R., & Ravi, V. (2015). Supplier selection in resilient supply chains: A grey relational analysis approach. *Journal of Cleaner Production, 86,* 343–359.

Rezaei, J., Kadziński, M., Vana, C., & Tavasszy, L. (2017). Embedding carbon impact assessment in multi-criteria supplier segmentation using ELECTRE TRI-rC. *Annals of Operations Research,* 1–23.

Rose, A. (2011). Resilience and sustainability in the face of disasters. *Environmental Innovation and Societal Transitions, 1*(1), 96–100.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15*(3), 234–281.

Sáenz, M. J., Revilla, E., & Acero, B. (2018). Aligning supply chain design for boosting resilience. *Business Horizons, 61*(3), 443–452.

Sahu, A. K., Datta, S., & Mahapatra, S. S. (2016). Evaluation and selection of resilient suppliers in fuzzy environment: Exploration of fuzzy-VIKOR. *Benchmarking: An International Journal, 23*(3), 651–673.

Sarkis, J. (1999). *How green is the supply chain? Practice and research*. Worchester: Graduate School of Management, Clark University.

Sawik, T. (2013). Selection of resilient supply portfolio under disruption risks. *Omega, 41,* 259–269.

Sawik, T. (2015). On the risk-averse optimization of service level in a supply chain under disruption risks. *International Journal of Production Research, 54*(1), 98–113.

Shaw, K., Shankar, R., Yadav, S. S., & Thakur, L. S. (2012). Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain. *Expert Systems with Applications, 39*(9), 8182–8192.

Song, H., Turson, R., Ganguly, A., & Yu, K. (2017). Evaluating the effects of supply chain quality management on food firms' performance: The mediating role of food certification and reputation. *International Journal of Operations & Production Management, 37*(10), 1541–1562.

Tang, C. S. (2006). Robust strategies for mitigating supply chain disruptions. *International Journal of Logistics: Research and Applications, 9*(1), 33–45.

Tavana, M., Yazdani, M., & Di Caprio, D. (2017). An application of an integrated ANP–QFD framework for sustainable supplier selection. *International Journal of Logistics Research and Applications, 20*(3), 254–275.

Torabi, S. A., Baghersad, M., & Mansouri, S. A. (2015). Resilient supplier selection and order allocation under operational and disruption risks. *Transportation Research Part E: Logistics and Transportation Review, 79,* 22–48.

Trapp, A. C., & Sarkis, J. (2016). Identifying robust portfolios of suppliers: A sustainability selection and development perspective. *Journal of Cleaner Production, 112,* 2088–2100.

Wang, X., Wu, Y., Liang, L., & Huang, Z. (2016a). Service outsourcing and disaster response methods in a relief supply chain. *Annals of Operations Research, 240,* 471–487.

Wang, P., Zhu, Z., & Wang, Y. (2016b). A novel hybrid MCDM model combining the SAW, TOPSIS and GRA methods based on experimental design. *Information Sciences, 345,* 27–45.

Weber, C. A., Current, J. R., & Benton, W. C. (1991). Vendor selection criteria and methods. *European Journal of Operational Research, 50*(1), 2–18.

Yazdani, M., Chatterjee, P., Zavadskas, E. K., & Zolfani, S. H. (2017). Integrated QFD–MCDM framework for green supplier selection. *Journal of Cleaner Production, 142*(4), 3728–3740.

Affiliations

Ahmed Mohammed[1] · Irina Harris[2] · Anthony Soroka[2] · Mohamed Naim[2] · Tim Ramjaun[2] · Morteza Yazdani[3]

Irina Harris
harrisi1@cardiff.ac.uk

Anthony Soroka
sorokaaj@cardiff.ac.uk

Mohamed Naim
naimmm@cardiff.ac.uk

Tim Ramjaun
ramjaunt@cardiff.ac.uk

Morteza Yazdani
myazdani@uloyola.es

[1] Faculty of Transport & Logistics, Muscat University, Building 142, Al Ghubra North, Muscat, Oman

[2] Cardiff Business School, Cardiff University, Aberconway Building, Colum Dr, Cardiff CF10 3EU, UK

[3] Management Department, Universidad Loyola Andalucia, Seville, Spain