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ORIGINAL RESEARCH

Sustainable supplier selection model with a trade-off between supplier development and supplier switching

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Abstract

Due to growing concerns regarding sustainability, purchasing decisions are challenging and difficult tasks for decision-makers. This difficulty has compelled purchasing companies to know and understand the whole purchasing process and to give importance to purchasing associated decisions. A long-term relationship and investment are required for purchasing decisions because they impact significantly on a company's performance and supply chain. Hence, supplier selection and sourcing strategy selection decisions are among a firm's most important problems. In this study, sourcing strategy decisions include supplier development, which helps suppliers to improve their performance, and supplier switching, which searches for more proficient alternatives for supply. To solve these problems, this study provides an integrated multi-criteria decision-making (MCDM) model. The model contains four stages. First, the right set of sustainable key performance indicators (SKPIs) for evaluating the performance of suppliers is identified through a literature survey and discussions with the decision-making team. Second, the best worst method-measurement of alternatives and ranking according to the compromise solution method (BWM-MARCOS) approach is applied to determine the priority weights of SKPIs and the priority weights of incumbent and new suppliers based on identified SKPIs. Third, a bi-objective mathematical model is developed to determine which optimum sourcing strategy and potential supplier should be chosen based on the priority of incumbent and new suppliers while optimizing cost and sustainable performance. Fourth, the mathematical model is solved using Epsilon constraint method and min–max fuzzy approach. The applicability and efficiency of the proposed integrated MCDM model is demonstrated with a real case study from a home appliance manufacturing company. The key findings reveal that the proposed model can be utilized for strategic and effective sourcing planning. One of the important contributions of this work is to provide suggestions for deciding the appropriate sourcing strategy for suppliers using the outputs of the mathematical model.

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1 Introduction

Over the years, procurement activities under the traditional arms' length theory have been practiced by buyers for achieving the lowest possible price from their suppliers (Rezaei, 2016). But this objective leads to a large base of suppliers, increased switching of orders from one supplier to another and short-term contracts. In the long run, this theory is not sufficient to stay competitive in the market as the large part of procurement activities support a company's inbound logistics and help in value creation (Rashidi et al., 2020). While traditional purchasing decisions are typically based only on cost, emerging market conditions integrate additional dimensions beyond the cost dimension. While Zero carbon or green focuses on environmental (Kannan et al., 2022a; Kannan et al., 2022b). Specifically, 'sustainability' is one popular dimension that has gained attention in purchasing decisions (Yazdani et al., 2021). Sustainability consists of economic, environmental, and social dimensions, also called the triple bottom line (3BL). Due to increasing interest and necessity of sustainability, a greater focus on purchasing decisions together with the aspects of sustainability is needed (Zhan et al., 2021).

A typical manufacturing company expends in purchasing inputs around 50% of its total earned revenue (Tong et al., 2022). Hence, over the long term, flawed decisions on procurement activities and a poor understanding of the cost of inputs will have a major impact on company performance, supply chain performance, and the financial stability of the company. Suppliers, being the foremost frontier of purchasing and supply management, emerge as important stakeholders in safeguarding companies from unsustainable behavior and their drive towards 3BL (Shang et al., 2022). Most of the time, unsustainable practices of suppliers affect the brand image and business of company negatively. For example, due to expired meat supplied by its suppliers in China, McDonald's, the largest food supply chain, has faced criticism worldwide; their burger products are suspended in sites such as Shanghai, China and some in the United States. In developing countries, other incidents are noteworthy. Between December 2005 and November 2006, Wal-Mart stores sold shrimp supplied by Thailand based supplier. The supplier, certified by the Global Aquaculture Alliance, was accused of labor abuse. This incident tarnishes the image of Wal-Mart only because of its supplier's action. Most of these and similar incidents highlight the lack of a well-structured procurement process in the forward supply chain and an improper installation of their suppliers. Hence, companies need to be more cautious in supplier base audit to evade the problems that may hamper their business and brand image. Also, there is often a conflict between sustainability and traditional objectives of the purchasing company because of customers, nonprofit organizations, and shareholders (Schramm et al., 2020). Hence, it is a major concern for purchasing companies specifically to know and understand the whole purchasing process when it comes to sourcing and supplier selection decisions.

Many multinational companies that function in developed countries rely on developing countries for their supply parts to attain low-cost advantage. Because some developing countries indulge in various unsustainable practices—child and bonded labor, poor health and safety, pollution production etc.—purchasing companies are not able to fulfill the customer's requirements (Alavi et al., 2021). Nevertheless, supplier selection decisions are crucial for purchasing companies in emerging economies to gain competitive advantage. Companies still struggle to decide if their suppliers can satisfy their requirements in terms of economic, environmental, and social aspects. As discussed through the examples, many companies face problems from the poor performance of their suppliers. Companies are always concerned whether their suppliers will fulfill their requirements, and if not, purchasing company decision-makers must evaluate what strategic sourcing decisions should be made. There are two sourcing strategies. The first strategy is supplier development. Supplier development entails all the activities that are necessary to improve the capabilities of suppliers. These activities include training sessions, resource sharing, joint capacity building, a strong information sharing system, machine upgrades, and so forth. To complete these activities, a supplier-specific and long-term investment is required, one that is distinct, cannot pass to another supplier easily, or be recovered by another buyer–supplier relationship. These investments provide long term benefits along with few risks (Sillanpää et al., 2015). The second strategy, termed supplier switching, consists of activities undertaken by the buying company to locate alternative sources of supply and to procure the raw material/semi-finished/ finished product from a more proficient supplier. Supplier switching is the process through which a company chooses to switch the incumbent supplier with a new supplier. The new supplier should be more capable than the incumbent suppliers on the specified company's requirements. While the enhanced capability is beneficial, this new relationship strategy does generate a risk because the alternate source of supply is essentially unknown for the company (Zhang et al., 2015). Thus, the decision of sourcing strategy selection for suppliers is complex. As supplier selection and sourcing strategy selection impacts the overall performance of company, these decisions are a notable challenge for the company.

The selection of these sourcing strategies is difficult for purchasing managers due to conflicts in objectives and performance measures of several suppliers (Ghadimi et al., 2017). Although many studies have explored the several approaches for supplier selection decisions, most of them are based on traditional parameters such as cost, lead time, reliability, etc. (Mukherjee, 2017). The exploration of environmental and social parameters in emerging economies is much less rare. This creates a need of a well-structured supplier performance evaluation framework and optimization model to handle the trade-off between conflicting objectives. Hence, in this study, we seek to mitigate this gap by providing the parameters of economic, environmental, and social dimensions with a reliable approach for evaluating the performance of suppliers on these parameters. An optimization model is developed for the optimal sourcing strategy selection for suppliers.

With this background in mind, this study addresses the following research questions: (1) What is the right set of SKPIs for evaluating the performance of suppliers? (2) What are the priorities of suppliers based on these SKPIs? and (3) Which optimum sourcing strategy and potential supplier should be chosen based on the priority of incumbent and new suppliers while optimizing cost and sustainable performance?

By answering the above-mentioned research questions, this study can fill the gaps identified in existing literature. Hence, the objectives of this study are framed as follows:

(a) To identify SKPIs for supplier performance evaluation.
(b) To develop and propose integrated BWM-MARCOS approach in determining the priority weights of SKPIs and priority weights of incumbent and new suppliers based on identified SKPIs.
(c) To build an optimization model to determine the optimum sourcing strategy and investment cost for each supplier while optimizing cost and sustainable performance.

The uniqueness of proposed optimization model lies in providing an integrated MCDM framework that can help manufacturing companies in making critical decisions of optimal selection of sourcing strategy, supplier selection, and investment cost for each supplier. The novelty of the model lies in minimizing cost and maximizing sustainable performance simultaneously. The novel integrated MCDM model that is developed consists of four stages. In stage 1, the SKPIs for supplier evaluation are identified. In the next stage, the SKPIs are evaluated using BWM. After that, an examination of suppliers with respect to SKPIs and a computation of the weights of both incumbent and new suppliers is done using MARCOS. In stage 3, an optimization model is developed to select the optimum sourcing strategies and suppliers as well as investment cost for each supplier. This model is based on the evaluation weights of incumbent and new suppliers while optimizing cost and sustainable performance. In the final stage, the optimization model is solved to provide optimal solutions by using Epsilon constraint method and fuzzy approach.

The remainder of the paper is structured as follows: Sect. 2 discusses the literature review related to the current study. Section 3 describes the addressed problem. Section 4 proposes a novel integrated MCDM model. The implementation of proposed model is pursued in Sect. 5. Section 6 provides discussion. Section 7 outlines managerial implications of the study. Section 8 summarizes the conclusion.

2 Literature review

In this study, the literature review is classified into four parts. The first part includes the literatures on performance evaluation indicators of suppliers. The second part presents the studies on sourcing decisions. The third part explores the works on supplier selection models. In the last, the research gap is discussed.

2.1 Performance evaluation indicators of suppliers

Suppliers play a critical role in the supply chain, and they have major impact on the performance of a company; accordingly, a rigorous and robust process is required for their evaluation and selection (Dey et al., 2015). Many studies have been proposed for supplier performance evaluation under traditional management environments (Bevilacqua & Petroni, 2002; Chen, 2011). For example, Dickson (1966) identified 23 traditional performance evaluation indicators for supplier evaluation and derived that quality, delivery, and performance history are top ranked performance indicators. Schmitz and Platts (2004) suggested a number of evaluation indicators, including suppliers' strategic planning, learning competence, coordination capability, information management, positiveness, priority decision capability, and relationship with other suppliers. In another study, Chen (2011) derived traditional key performance evaluation indicators for supplier evaluation decisions. Based on a comprehensive review, quality, technology and production, organization management and cost are considered as essential evaluation indicators for supplier performance evaluation in their study. Although the choice of traditional performance indicators for supplier evaluation is still crucial, with an increasing concern towards sustainability, companies seek sustainability and evaluate their suppliers through sustainable lens (Zimmer et al., 2016; Bartos et al., 2022). This incorporates the triple bottom line approach that consists of economic, environmental, and social dimensions in the supplier evaluation process, and it embraces a broader range of evaluation indicators for suppliers. Many studies have identified the need for environmental and social indicators in supplier evaluation and selection decisions (Jain & Singh, 2020; Luthra et al., 2017; Orji & Wei, 2015; Vahidi et al., 2018). Ghadimi et al. (2017) reported environmental and social key performance indicators based on supply chain practices for supplier selection. They presented four main indicators by which performance is gauged in the environmental dimension: green image, pollution control, green competencies, and green design. For the social dimension, the main performance indicators include health and safety, employment practices, local community influence, and contractual stakeholders' influence. However, social sustainability performance differs due to the diversity of trends and traits all over the world; computing social performance is more difficult than ranking economic or environmental dimensions (Mani et al., 2014). Hence, Bai et al. (2019) proposed a study to provide social sustainability indicators for supplier evaluation. A lack of uniformity of indicators in supplier performance evaluation process can be clearly seen in the existing literature. In this study, key performance indicators for sustainable supplier performance evaluation and selection are provided; our resources have strategic intent and are based on the requirements of the business and the company to fill this gap.

2.2 Sourcing decisions

Over the years, academic attention to sourcing decisions, particularly in the research area of supplier selection, has increased due to global competitiveness (Burke et al., 2009). Glock et al. (2017) addressed the importance of suppliers by considering their key role in the buying company's performance. They stated that with limited alternatives, suppliers' performance directly affects the competitive position of the company. Sourcing decisions should be based on conditions that align with the requirements and goals of the company (Merzifonluoglu, 2015). Whenever a supplier is not able to satisfy the requirements of the buying company, two sourcing decisions are considered: either supplier development or supplier switching options are researched in the literature (Friedl & Wagner, 2012). Many studies address supplier development (Blome et al., 2014; Humphreys et al., 2004; Modi & Mabert, 2007) and supplier switching (Demski et al., 1987; Wanger and Friedl, 2007; Zhang et al., 2015) individually. For supplier development, Xu and Xiang-Yang (2007) developed a model for supplier selection under supplier development orientation. Calvi et al. (2010) explored supplier evaluation and selection for strategic supplier development. Diouf and Kwak (2018) proposed a framework for supplier selection and development in the publishing and printing industry. In addition, van der Westhuizen and Ntshingila (2020) examined the effect of supplier development on company's business performance. On the other hand, Wanger and Friedl (2007) proposed a research study on supplier switching as a sourcing decision for purchasing the product. Wu (2009) analyzed supplier selection under consideration of supplier switching options. Mir et al. (2017) observed a phenomenon that addresses the inertness of supplier switching decision. Uluskan et al. (2017) studied supplier switching decisions that influenced the cost effective and competitive strategies of buying company. Holma et al. (2021) conceptualized a theoretical framework for the supplier switching decision process. There are few studies that considered both sourcing strategies collectively in the literature. Friedl and Wanger (2012) proposed a study that compares supplier development and supplier switching strategies simultaneously. Jafarian et al. (2021) studied the problematic suppliers under risk and decided the best option by considering both strategies. As discussed, most studies are empirical or theoretical in nature and the adoption of sustainability with these sourcing decisions is uncommon in literature. To bridge this gap, this study proposed an integrated MCDM model that will provide the answer for a sourcing strategy of each supplier of the buying company under sustainability.

2.3 Supplier selection models

In the literature, since supplier are assessed from different viewpoints, several multi-criteria decision-making (MCDM) models have been proposed for supplier selection. Zimmer et al. (2016) reviewed a literature of various supplier selection models in the view of sustainability and concluded that most of the models are MCDM based. There are number of studies that have utilized individual decision-making models; some involve AHP (Mani et al., 2014), ANP (Önder & Kabadayi, 2015), TOPSIS (Boran et al., 2009), BWM (Rezaei et al., 2016), DEMATEL (Hsu et al., 2013; Kannan, 2021), ISM (Sonar et al., 2022), VIKOR (Amiri et al., 2011), DEA (Dobos & Vörösmarty, 2014), ELECTRE (Fei et al., 2019), QFD (Tidwell & Sutterfield, 2012), PROMETHEE (Abdullah et al., 2019), mathematical programming (Kazemi et al., 2015), fuzzy set theory (Amid et al., 2011), neural networks (Thongchattu & Siripokapirom, 2010) and genetic algorithms (Hashim et al., 2017). Apart from these individual MCDM models, lots of studies on integrated models have been proposed such as AHP-Entropy-TOPSIS (Freeman & Chen, 2015), QFD-ANP (Bottani et al., 2018), BWM-COPRAS (Qin & Liu, 2019), DEA-PCA-VIKOR (Karami et al., 2021), Fuzzy-entropy (Rahimi et al., 2021), Neural networks—Fuzzy VIKOR (Bahadori et al., 2020), Fuzzy AHP - TOPSIS - FIS (Mina et al., 2021), Fuzzy AHP- DEMATEL (Lahane & Kant, 2021), etc. Some recent research examples on supplier selection models are cited. Hamdan and Cheaitou (2017) proposed a three-stage supplier selection model in which fuzzy TOPSIS-AHP is utilized for computing the weights of suppliers and the weighted comprehensive criterion method, the branch-and-cut algorithm is utilized to solve the optimization model for supplier selection. Mohammed et al. (2019) developed a hybrid MCDM-model (FAHP-TOPSIS-Epsilon constraint) to solve the supplier selection problem. Rezaei et al. (2020) constructed a four-phase MCDM model in which FAHP is applied to evaluate the performance of suppliers, and mathematical programming is utilized to select the supplier. However, the existing studies described models to rank or select them without considering the supplier development cost and supplier switching cost. Further, no study develops a hybrid MCDM model that considers the selection of sourcing strategy along with supplier selection. To address this gap, a novel supplier selection model is proposed in this study that utilizes BWM-MARCOS to determine the priority weights of SKPIs and priority weights of incumbent and new suppliers based on identified SKPIs and Epsilon constraint method; a min–max fuzzy approach is applied to provide optimal solutions of the bi-objective optimization model. Hence, the novelty of this paper is that it brings different OR techniques together an applied context of supplier selection and supplier sourcing strategy selection models.

3 Research gap

A few gaps are addressed in the above discussed literature. These are summarized as follows:

(i) The selection of appropriate suppliers for procuring raw material/components/semi-finished goods/finished goods serves as a noticeably strategic decision for any company. In this domain, the literature reveals a lack of uniformity in defining the assessment and selection process of suppliers and in identifying performance indicators of suppliers to select the best supplier. Hence, this study contributes by providing the right and uniform set of key performance indicators for sustainable supplier performance evaluation and selection that can fulfill the requirements of the business and the company.

(ii) As discussed, the most of studies select the best supplier without considering sourcing decisions of supplier development and supplier switching in literature. The contribution of this research is done by providing an integrated MCDM model that will help decision makers in deciding the appropriate sourcing strategy for the suppliers of the buying company in the view of sustainability.

None of the reviewed studies built an optimization model that can determine the optimum sourcing strategy and investment cost for each supplier while optimizing cost and sustainable performance. This gap is overcome in this study by developing the optimization model under the same mentioned conditions.

4 Case description

The problem of an India-based home appliance manufacturing company of washing machine products is considered in this study. It has multiple facilities throughout India. The case company is sustainability driven and committed towards customer satisfaction by providing high quality goods and services. To avoid disclosure of the original identity of the manufacturing company, it is simply called 'XYZ' company throughout this study. Its turnover is recorded at around 5,000 crore rupees in the financial year 2019–2020 and more than 2000 people are engaged in its workforce. Its supply chain consists of suppliers, manufacturers, distributors, retailers, and end customers. The company offers refrigerators, washing machines, air conditioners, microwave ovens, purifiers, and kitchenware. The raw material/components are procured from suppliers by manufacturers, and the manufacturers facilitate an infrastructure to generate the finished products. Further, these products are sent to end customers via distributors and retailers. XYZ has a well-structured manufacturing process, extensive distribution network, and a good reputation in the market; its main SC strategy is customer responsiveness. There is a continuous monitoring and review process for all the operations in place which provides check points to XYZ for continuous improvement. As per its last audit result, the operational and financial performance of the company is above satisfactory. However, it has indicated few issues in the procurement procedure of their washing machine product, resulting in increased customer queries. The washing machine product is made up of 210 components. These components are classified into 8 classes such that components of similar nature are grouped together and are procured from the same set of suppliers. These classes are 'Cabinet', 'Drum', 'Timer with harness', 'Motor', 'Aesthetical' and 'Small auxiliary parts', 'PP tub' and 'Rubber parts'. XYZ plans to look into the process of procurement of components in detail for all areas for scope of improvement. The company is already involved in periodic evaluation and monitoring of its suppliers to gain competitive advantage in the market. Detailed analysis and discussion of results of evaluation has suggested that some suppliers of certain classes of components are not able to fulfill company's needs with respect to traditional attributes such as cost, quality, delivery, or service while some others are not following the protocols pertaining to environmental regulations and social norms.

Evidently, this calls for XYZ to focus on supplier selection strategies such as switching the incumbent non-performing suppliers with new ones and supplier development for long term relationship and partnership enhancement. In supplier development process, XYZ has to develop a supplier specific and cooperative investment package that is distinctive in nature and cannot be transferred to other suppliers or recovered in other supplier partnerships/relationships. In contrast, supplier switching would require XYZ to find an alternate supplier and to purchase components from this more capable supplier. The matter of concern which arises at this point is whether investment should be done in ‘supplier development’, to opt for ‘supplier switching,’ or to pursue a combination of both. Additionally, as all the classes of components of the washing machine are procured from the same suppliers, this decision has multi-fold impact on the SC performance. The advantage and success of each strategy depends on the nature of the case, available set of suppliers, performance level of suppliers, economic strength of the company, and willingness of suppliers to improve. Hence, to understand which sourcing strategy is best suited for our case study, a thorough research and analysis is required.

To maintain sustainability drive of case company, the performance evaluation of suppliers must be based on performance indicators that includes economic, environmental, and social dimensions such as quality, delivery, pollution production, resource consumption, health and safety, and the right of stakeholders. Further, the process of performance evaluation of suppliers with respect to SKPIs must incorporate the experts’ opinions to handle the conflicting nature of SKPIs. Clearly, it is a multi-dimensional problem where simultaneous consideration of multiple conflicting SKPIs for supplier’s performance evaluation are required along with an effective group decision making team of experts. In addition, these decisions must be integrated with other supply chain decisions such as production, inventory, and transportation, and they must be reached with the aim to simultaneously minimize the cost and maximize the sustainable performance of suppliers.

This calls for development of a supplier performance evaluation framework and optimization model to capture the trade-off between two conflicting objectives. Hence, the main aim of the study is to develop a supplier performance evaluation framework and build an optimization model to choose the appropriate sourcing strategy and investment cost for each supplier. To address the problem faced by the case company, a four-stage novel integrated MCDM model is proposed to accomplish supplier selection and appropriate sourcing strategy selection as well as making a cost-effective trade-off between sourcing strategies. In the first stage, SKPIs are identified for performance evaluation of potential suppliers. Further, integrated BWM-MARCOS approach is utilized for determining the priority weights of suppliers with respect to SKPIs. An optimization model is developed for the selection of suppliers and their respective sourcing strategies based on their performance on SKPIs in the third stage. In the last, Epsilon constraint method and fuzzy approach is utilized to provide the solution of optimization model. This model is elaborated in detail in Sect. 4.

5 Proposed integrated MCDM model

In this section, a novel model is proposed for selection of suppliers and their respective sourcing strategy with the aim of achieving a trade-off between objective functions and minimizing the cost and maximizing the sustainable performance of suppliers. The novel model is developed in following four stages: (i) identification of sustainable key performance indicators for supplier performance evaluation; (ii) determination of priority weights of suppliers; (iii) development of optimization model; (iv) solution approach for optimization model.

The supplier evaluation problem is represented as follows:

There are I incumbent suppliers, which are part of the set $I = \{SI_i, i = 1, 2, \ldots, I\}$, from whom the manufacturer would consider collaborative purchasing in the near future. Also, J new suppliers (in case of switching), are part of set $N = \left\{SN_j, j = 1, 2, \ldots, J\right\}$, defined for the same purpose.

The main target of this decision integrated MCDM model is for determining the priority weights of each supplier and selecting the appropriate suppliers as well as their respective sourcing strategy based on this proposed novel model.

Initially, the SKPIs are identified to evaluate the performance of potential set of suppliers. In the second stage, an integrated BWM-MARCOS approach is utilized for evaluation of supplier's performance based on a number of economic, environmental, and social SKPIs. Here, BWM is applied for evaluation of SKPIs and MARCOS is utilized for supplier's performance evaluation with respect to SKPIs. Next, a mixed integer linear programming mathematical model is formulated for the selection of suppliers and their respective sourcing strategies taking into account their performance on SKPIs. The multi-objective model decides the optimum sourcing strategy for each incumbent supplier, development areas of retrained incumbent supplier and investment planning for sourcing strategies. In the last stage, to generate the Pareto solutions of the multi objective model, Epsilon-constraint method is utilized. Then a fuzzy technique is applied to choose the optimal solution. To understand the basic concept of utilized methods in proposed model, a brief background discussion is available in "Appendix A". The schematic view of proposed integrated MCDM model is shown in Fig. 1. The novelty of this figure is in developing an integrated MCDM model for helping manufacturing companies make crucial decisions of optimal sourcing strategy selection, supplier selection, and investment cost planning for each supplier as well as in minimizing cost and maximizing sustainable performance of suppliers simultaneously.

A detailed discussion of the stages involved in the proposed integrated MCDM model is represented below.

5.1 Stage 1: Identification of SKPIs for supplier performance evaluation

The purpose of stage 1 is to identify SKPIs for supplier performance evaluation that play an important role in supplier selection procedure and their performance assessment.

(a) **Formation of decision-making team for supplier evaluation**
Initially, an expert panel is formed. K experts, denoted by set $DM = \{DM_k, k = 1, 2, \ldots, K\}$, are selected from various departments to assist the expert panel in their decision making.

(b) **Identification of SKPIs for supplier evaluation**
Further, the identification of SKPIs procedure begins with the help of literature and decision- making team. U SKPIs are denoted by the set of supplier performance evaluation indicators, $SKPI = \{SKPI_u, u = 1, 2, \ldots, U\}$ are identified. These SKPIs are divided into three categories: economic, environmental, and social (c = 1,2,3). The set of three categories SKPIs are denoted by $SKPI^{Eco} = \left\{SKPI_l^{Eco}, l = 1, 2, \ldots, L, l \subseteq u\right\}$, $SKPI^{Env} = \left\{SKPI_m^{Env}, m = 1, 2, \ldots, M, m \subseteq u\right\}$, and $SKPI^{Soc} = \left\{SKPI_n^{Soc}, n = 1, 2, \ldots, N, n \subseteq u\right\}$ respectively.

5.2 Stage 2: Determination of priority weights of suppliers

In this stage, the purpose is to achieve an appropriate approach to compute priority weights of suppliers with respect to identified SKPIs. BWM is used to calculate the weights of these SKPIs and then MARCOS is used to obtain the priority weights of suppliers with respect to each key performance indicator and aggregated priority wights of supplier. The detailed

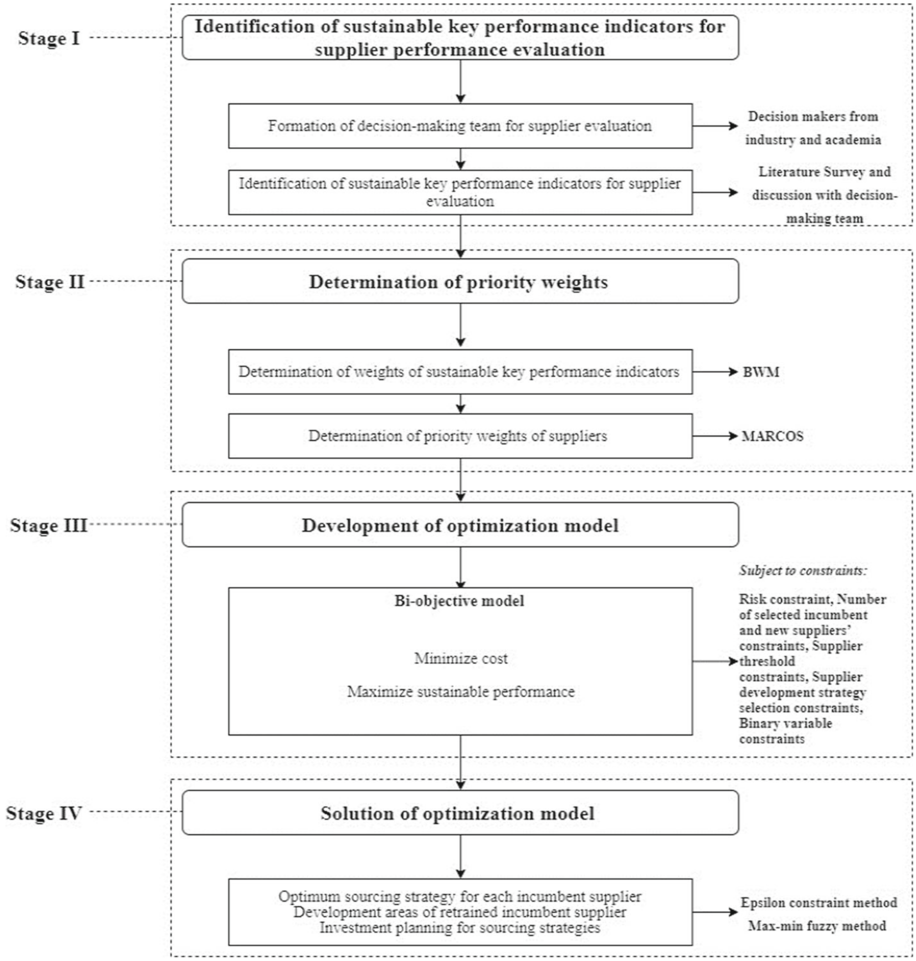


Fig. 1 Proposed integrated MCDM model

explanation of BWM and MARCOS is given in "Appendix A" (see section A.1.1.1, section A.1.1.2).

5.3 Stage 3: Development of optimization model

In this study, a multi-objective optimization model is developed to decide the optimal sourcing strategy for each supplier with respect to their sustainable performance and investment cost. The objectives are minimization of the cost and maximization of sustainable impact/performance. The assumptions, description of indices, parameters and variables as well as the formulation of the model are presented as follows:

Index

i	Set of incumbent suppliers
j	Set of new suppliers
u	Set of sustainable key performance indicators
v	Set of development stages

Parameters

C_{iuv}^{Devlop}	Development cost of vth development stage for ith incumbent supplier with respect to uth SKPI
C_j^{Switch}	Financial loss due to switching to jth new supplier
C_j^{Risk}	Cost of reducing per unit risk of switching to jth new supplier
W_i^{Inc}	Weight of ith incumbent supplier
W_j^{New}	Weight of jth new supplier
W_{iu}^{Inc}	Weight of ith incumbent supplier with respect to uth SKPI
$Wbreak_u$	Break value of uth SKPI for development strategy
W_{THu}	Threshold of weight for supplier selection
N^{Total}	Total required number of suppliers
R_j^{New}	Risk of building new relationship with jth supplier
R	Maximum allowable risk to build new relationship
n'_T	Total required number of SKPIs that satisfy condition ($W_{iu}^{Inc} \geq W_{THu}$) for incumbent supplier retention
Q_u	$\begin{cases} 1 & if\ u\text{th } SKPI \text{ can be developed} \\ 0 & otherwise \end{cases}$

Variables

X_i^{Inc}	$\begin{cases} 1 & i\text{th incumbent supplier is retained} \\ 0 & i\text{th incumbent supplier is switched} \end{cases}$
Y_j^{New}	$\begin{cases} 1 & j\text{th new supplier is selected} \\ 0 & \text{otherwise} \end{cases}$
Z_{iuv}^{Inc}	$\begin{cases} 1 & \text{If } i\text{th incumbent supplier lies within } v\text{th development stage with respect to } u\text{th SKPI} \\ 0 & \text{otherwise} \end{cases}$
N^{Inc}	Number of selected incumbent suppliers

X_{iu}^{Inc}	$\begin{cases} 0 \text{ The weight of } i\text{th incumbent supplier with respect to } u\text{th SKPI is greater than than the thresold weight of } u\text{th SKPI} \\ 1 \text{ otherwise} \end{cases}$
P_i	The sum of X_{iu}^{Inc} for $i$thincumbent supplier

Objective Functions:

$$\text{Min } Z_1 = \sum_i \sum_u \sum_v C_{iuv}^{Devlop} Z_{iuv}^{Inc} Q_u + \sum_j C_j^{Switch} Y_j^{New} + \sum_j C_j^{Risk} R_j^{New} Y_j^{New} \quad (1)$$

The objective Z_1 aims to minimize the sum of development cost with respect to each development key performance indicator for each retained incumbent supplier. This includes financial loss due to switching to a new supplier (i.e., travel cost, lost time cost due to travel, internal inspection cost, external inspection cost, internal test cost, external test cost, print change cost, tooling and amortization cost) and the cost of reducing risk generated by switching to a new supplier.

$$\text{Max } Z_2 = \sum_i \sum_u W_{iu}^{Inc} X_i^{Inc} + \sum_j W_j^{New} Y_j^{New} \quad (2)$$

The objective Z_2 aims to maximize the sustainable performance of suppliers. To this aim, the weights of suppliers are obtained by MARCOS method.

Constraints:

Risk constraint

$$\sum_j R_j^{New} Y_j^{New} \leq R \quad (3)$$

This constraint ensures that the risk of building relationship with new suppliers is less than or equal to the maximum allowable risk of relationship development with new suppliers.

Number of selected incumbent and new suppliers' constraints

$$\sum_i X_i^{Inc} = N^{Inc} \quad (4)$$

$$\sum_j Y_j^{New} = N^{Total} - N^{Inc} \quad (5)$$

These constraints ensure the total number of selected incumbent and new suppliers should be equal to the total required number of suppliers.

Supplier threshold constraints

$$\left(W_{iu}^{Inc} - W_{THu}\right)\left(X_{iu}^{Inc}\right) + (W_{THu} - W_{iu}^{Inc})\left(1 - X_{iu}^{Inc}\right) \geq 0 \quad \forall i, u \quad (6)$$

$$P_i = \sum_u X_{iu}^{Inc} \quad \forall i \quad (7)$$

$$\left(P_i - n'_T\right) * X_i^{Inc} + \left(n'_T - P_i\right) * \left(1 - X_i^{Inc}\right) \geq 0 \quad \forall i \quad (8)$$

These constraints ensure that the weight of retained incumbent supplier should be greater than or equal to threshold weight.

Supplier development strategy selection constraints

$$\sum_{v=1}^{V}(v-1)Wbreak_u\left(Z_{iuv}^{Inc}\right)Q_u \le W_{iu}^{Inc}X_i^{Inc} \le \sum_{v=1}^{V} vWbreak_u Z_{iuv}^{Inc} Q_u \quad \forall i, u \tag{9}$$

$$\sum_{v=1}^{V} Z_{iuv}^{Inc} \le X_i^{Inc} \quad \forall i, u \tag{10}$$

These constraints decide the development stage of each development key performance indicator for each retained incumbent supplier.

5.4 Stage 4: Solution of optimization model

In the Multiple Objective Decision Making (MODM) problem, the simultaneous optimization of all conflicting objectives subject to constraints is quite difficult. In this regard, the Epsilon-constraint method is applied to solve the proposed optimization model and to find a set of feasible solutions (Pareto solutions). The steps of Epsilon-constraint method are outlined in "Appendix A" (see section A.1.2.1). To decide the best compromised solution from the generated Pareto optimal solutions, a max–min fuzzy method is utilized. In "Appendix A" (see section A.2), a detailed discussion of the max–min fuzzy method is provided.

6 Proposed model implementation

The main aim of the proposed integrated MCDM model is to resolve a procurement problem of washing machine products in an Indian home appliance manufacturing firm. The considered problem is described in detail in Sect. 3. The proposed integrated model provides a well-defined supplier performance evaluation framework and an optimization model for choosing the appropriate sourcing strategy and investment cost for each supplier while simultaneously optimizing objectives (minimizing cost and maximizing sustainable performance) of suppliers. In this section, the application of proposed integrated model is illustrated. The details of suppliers considered in the case study are as follows: 11 incumbent suppliers are defined, part of the set $SI = \{SI_i, i = 1, 2, \ldots, 11\}$ from whom the case company would consider collaborative purchasing. Also, 5 new suppliers (in case of switching), part of the set $SN = \{SN_i, i = 1, 2, \ldots, 5\}$ are defined for the same purpose. The detailed proposed integrated model implementation is given as follows:

6.1 Stage 1: Identification of SKPIs for supplier performance evaluation

The purpose of stage 1 is to identify SKPIs for supplier performance evaluation that plays an important role in supplier selection procedure and their performance assessment.

(a) Formation of decision-making team for supplier evaluation

Initially, an expert panel is formed. The selected members of expert panel are experienced, familiar with the current study and work within the case company. Five experts, denoted by set $DM = \{DM_a, a = 1, 2, \ldots, 5\}$, are selected for this study.

(b) Identification of sustainable SKPIs for supplier evaluation

Further, for evaluating these suppliers, a set of SKPIs is derived from the literature survey and discussion with expert panel. 17 SKPIs, denoted by set SKPIs

$= \{SKPI_U, U = 1, 2, \ldots, 17\}$ are finalized and divided into three categories (economic, environmental, and social) sub-SKPIs. The set of economic, environmental, and social sub-SKPIs are $SKPI^{Eco} = \{SKPI_L^{Eco}, L = 1, 2, \ldots, 8\}$, $SKPI^{Env} = \{SKPI_M^{Env}, M = 1, 2, \ldots, 6\}$, and $SKPI^{Soc} = \{SKPI_N^{Soc}, N = 1, 2, 3\}$ respectively. The final list of SKPIs is presented in Table 1.

Table 1 The list of SKPIs for supplier performance evaluation

	SKPIs	Definition	References
Economic KPIs	Price	Supply the component/product at admissible price that includes processing cost, holding cost, purchasing cost, and warranty cost	Luthra et al. (2017), Wu et al. (2016)
	Quality	Provide an exclusive quality leveled component/product as per supplier quality agreement and have relevant all quality certificates	Badri Ahmadi et al. (2017), Luthra et al. (2017)
	Delivery	Meet on-time and in-full delivery order schedules	Jain and Singh (2020), Kaur et al. (2016)
	Technical Capability	Acquire technical resources and new technologies for R&D processes and practices	Lutra et al. (2017), Lee et al. (2015)
	Flexibility	Adapt to predictable or unpredictable changes	Luthra et al. (2017), Roy et al. (2020)
	Financial Position	Financial condition and profitability in the market	Zimmer et al. (2016)
	Geographical Location	Risk level of geographic region and distance from manufacturing facility	Jain and Singh (2020), Memari et al. (2019)
	Market Reputation	Past cooperation experience, level of trust and reputation in the market	Stević et al. (2020), Vasiljević et al. (2018)
Environmental KPIs	Pollution Production	Released amount of pollution per time unit consists of wastewater, air emissions, solid waste, and harmful materials	Nielsen et al. (2014)
	Pollution Control	Control activities for the amount of pollution releases to the environment	Jain and Singh (2020), Memari et al. (2019), Tavana et al. (2017)
	Resource Consumption	Proper use of resources such as material and energy	Jain and Singh (2020), Zimmer et al. (2016, Sharma et al. (2022))

Table 1 (continued)

	SKPIs	Definition	References
	Environmental management system	Implementation of processes and practices such as Environment protection system certifications, environmental policies and planning, reverse logistics system, environmental implementation and operation and regulatory compliance that reduce the negative impact on environment and increase operating efficiency	Roy et al. (2020), Luthra et al. (2017),
	Green competencies	Practice on competencies such as clean technology, use of eco-friendly material in supplied component/product to reduce the impact on natural resources	Memari et al. (2019)
	Green innovativeness	Capability in green design and Green R&D to reduce the deterioration of the environment while optimizing the use of natural resources	Luthra et al. (2017)
Social KPIs	Safety and health	The safety, health and welfare of the people engaged at supplier's workplace	Roy et al. (2020), Memari et al. (2019; Zarbakhshnia et al. (2022))
	The interests and rights of employees	Concerns with the employees' related factors and requirements to achieve sustainable effectiveness in the long term	Memari et al. (2019), Luthra et al. (2017),
	The rights of stakeholders	Concerns with the moral rights of society having stakes in the business	Roy et al. (2020), Jain and Singh (2020)

Due to financial restrictions and the nature of key performance indicators, incumbent suppliers cannot get developed at each key performance indicator. Hence, SKPIs are identified from the list of identified key performance indicators the company wants to develop for supplier performance enhancement. That list may include quality, delivery, technical capability, flexibility, pollution production, pollution control, environmental management system, green innovativeness, safety and health, the interests and rights of employees, and the rights of stakeholders.

6.2 Stage 2: Determination of priority weights of suppliers

In this stage, the purpose is to achieve an appropriate approach to compute priority weights of suppliers with respect to identified SKPIs. BWM is used to calculate the weights of these SKPIs and then MARCOS is used to obtain the priority weights of suppliers with respect to each key performance indicator and aggregated priority weights of suppliers. The detailed explanation of these steps is given as follows:

(a) **Determination of weights of SKPIs using BWM**

For determining the priority weights of SKPIs, 5 experts who work with the case company are interviewed to collect the pairwise comparison matrix data for BWM. Next, the priority weights of categories and SKPIs with respect to each category are computed using the BWM process as explained in "Appendix A" (see section A.1.1.1) for each expert. For the final weights, aggregation is done by using simple average. The results are consistent as the consistency ratios are almost close to zero. The procedure of determination of weights of SKPIs is explained briefly as follows:

Initially, the steps of BWM are performed for the KPIs of first category (economic). The final optimal weights of the KPIs of economic category are $w_1^{Eco} = 0.126, w_2^{Eco} = 0.312, w_3^{Eco} = 0.233, w_4^{Eco} = 0.103, w_5^{Eco} = 0.080, w_6^{Eco} = 0.051, w_7^{Eco} = 0.044 \text{and} w_8^{Eco} = 0.052$. Similarly, the weights of the KPIs for the environmental category, $w_1^{Env} = 0.141, w_2^{Env} = 0.204, w_3^{Env} = 0.077, w_4^{Env} = 0.402, w_5^{Env} = 0.096$ and $w_6^{Env} = 0.081$, and the weights of the KPIs of the social category, $w_1^{Soc} = 0.631, w_2^{Soc} = 0.258 \text{and} w_3^{Soc} = 0.112$, are calculated. These weights are shown in Fig. 2.

Further, the procedure is repeated for three categories and that determined the optimal weighting vector $\left(w^{Eco} = 0.731, w^{Env} = 0.203, w^{Soc} = 0.065\right)$ as shown in Fig. 3.

The global weights of each SKPI are computed as explained in section A.1.1.1, i.e., $w_1^{SKPI} = 0.092, w_2^{SKPI} = 0.228, w_3^{SKPI} = 0.170, w_4^{SKPI} = 0.075, w_5^{SKPI} = 0.058, w_6^{SKPI} = 0.037, w_7^{SKPI} = 0.032, w_8^{SKPI} = 0.038, w_9^{SKPI} = 0.029, w_{10}^{SKPI} = 0.041$ $w_{11}^{SKPI} = 0.016, w_{12}^{SKPI} = 0.082, w_{13}^{SKPI} = 0.020, w_{14}^{SKPI} = 0.016, w_{15}^{SKPI} = 0.041, w_{16}^{SKPI} = 0.017, w_{17}^{SKPI} = 0.007$. The global weights of each SKPI are presented in Fig. 4.

(b) **Determination of priority weights of suppliers using MARCOS**

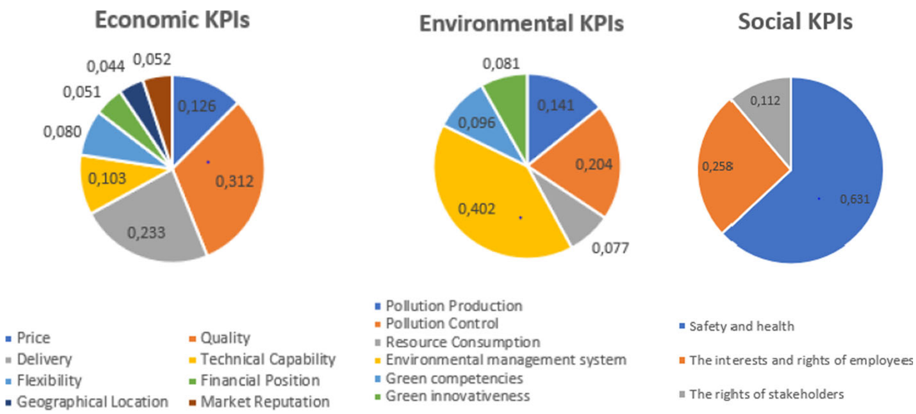


Fig. 2 The priority weights of SKPIs with respect to each category

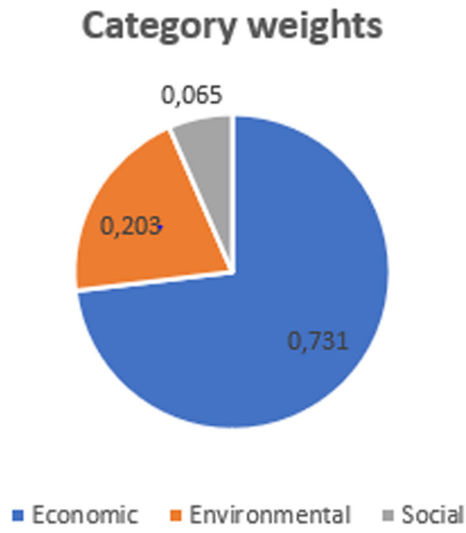


Fig. 3 Priority weights of SKPI categories

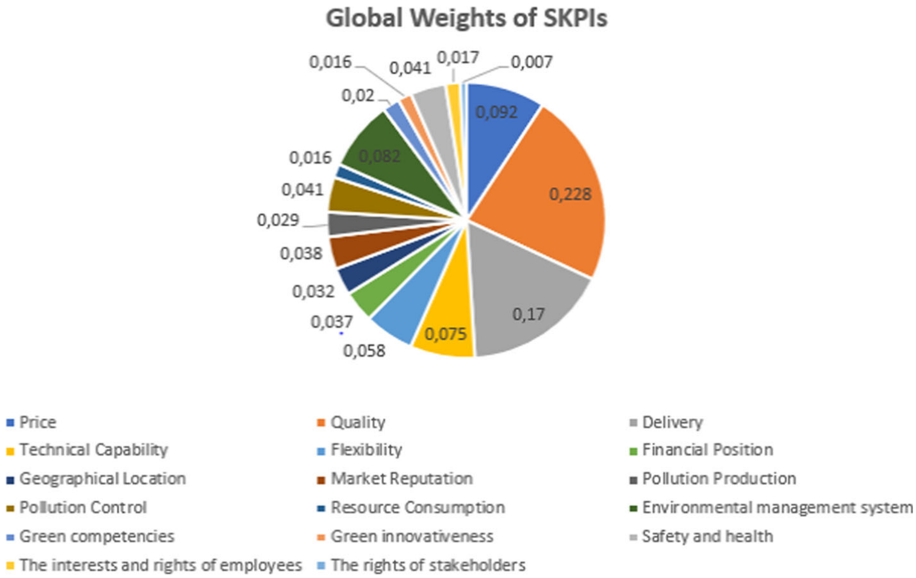


Fig. 4 The global weights of SKPIs

After computing the weights of SKPIs, the application of MARCOS method, a decision matrix is developed for incumbent suppliers and new suppliers with respect to each expert. Next, the opinions of all experts are aggregated by taking average to form the initial decision matrix. Further, extended matrix is determined by computing AI and AAI solutions. Here, Price is treated as the cost SKPI while the remaining SKPIs are classified under the benefit SKPI group. By applying step 3 of section A.1.1.2, the extended matrix is normalized. Next, the weighted normalized matrix is computed by multiplying all the values of the normalized matrix with the priority weights of SKPIs, i.e., the output of BWM. The determined weights of incumbent suppliers with respect to each SKPI are $W_{11}^{Inc} = 0.245$, $W_{12}^{Inc} = 0.035$, W_{13}^{Inc}

$= 0.041$, $W_{14}^{Inc} = 0.023$, $W_{15}^{Inc} = 0.036$, $W_{16}^{Inc} = 0.016$, $W_{17}^{Inc} = 0.036$, $W_{18}^{Inc} = 0.016$, $W_{19}^{Inc} = 0.066$, $W_{110}^{Inc} = 0.032$, $W_{111}^{Inc} = 0.047$, $W_{112}^{Inc} = 0.023$, $W_{113}^{Inc} = 0.039$, $W_{114}^{Inc} = 0.047$, $W_{115}^{Inc} = 0.033$, $W_{116}^{Inc} = 0.033$, $W_{117}^{Inc} = 0.024$, $W_{21}^{Inc} = 0.069$, $W_{22}^{Inc} = 0.079$, $W_{23}^{Inc} = 0.079$, $W_{24}^{Inc} = 0.081$, $W_{25}^{Inc} = 0.081$, $W_{26}^{Inc} = 0.080$, $W_{27}^{Inc} = 0.081$, $W_{28}^{Inc} = 0.080$, $W_{29}^{Inc} = 0.048$, $W_{210}^{Inc} = 0.050$, $W_{211}^{Inc} = 0.047$, $W_{212}^{Inc} = 0.041$, $W_{213}^{Inc} = 0.039$, $W_{214}^{Inc} = 0.030$, $W_{215}^{Inc} = 0.043$, $W_{216}^{Inc} = 0.033$, $W_{217}^{Inc} = 0.062$, $W_{31}^{Inc} = 0.069$, $W_{32}^{Inc} = 0.079$, $W_{33}^{Inc} = 0.079$, $W_{34}^{Inc} = 0.081$, $W_{35}^{Inc} = 0.081$, $W_{36}^{Inc} = 0.080$, $W_{37}^{Inc} = 0.081$, $W_{38}^{Inc} = 0.080$, $W_{39}^{Inc} = 0.109$, $W_{310}^{Inc} = 0.113$, $W_{311}^{Inc} = 0.106$, $W_{312}^{Inc} = 0.113$, $W_{313}^{Inc} = 0.109$, $W_{314}^{Inc} = 0.106$, $W_{315}^{Inc} = 0.118$, $W_{316}^{Inc} = 0.120$, $W_{317}^{Inc} = 0.120$, $W_{41}^{Inc} = 0.042$, $W_{42}^{Inc} = 0.130$, $W_{43}^{Inc} = 0.130$, $W_{44}^{Inc} = 0.126$, $W_{45}^{Inc} = 0.140$, $W_{46}^{Inc} = 0.138$, $W_{47}^{Inc} = 0.140$, $W_{48}^{Inc} = 0.138$, $W_{49}^{Inc} = 0.109$, $W_{410}^{Inc} = 0.113$, $W_{411}^{Inc} = 0.106$, $W_{412}^{Inc} = 0.113$, $W_{413}^{Inc} = 0.109$, $W_{414}^{Inc} = 0.106$, $W_{415}^{Inc} = 0.118$, $W_{416}^{Inc} = 0.120$, $W_{417}^{Inc} = 0.120$, $W_{51}^{Inc} = 0.245$, $W_{52}^{Inc} = 0.029$, $W_{53}^{Inc} = 0.029$, $W_{54}^{Inc} = 0.029$, $W_{55}^{Inc} = 0.023$, $W_{56}^{Inc} = 0.035$, $W_{57}^{Inc} = 0.029$, $W_{58}^{Inc} = 0.042$, $W_{59}^{Inc} = 0.022$, $W_{510}^{Inc} = 0.041$, $W_{511}^{Inc} = 0.038$, $W_{512}^{Inc} = 0.032$, $W_{513}^{Inc} = 0.031$, $W_{514}^{Inc} = 0.047$, $W_{515}^{Inc} = 0.043$, $W_{516}^{Inc} = 0.033$, $W_{517}^{Inc} = 0.024$, $W_{61}^{Inc} = 0.069$, $W_{62}^{Inc} = 0.079$, $W_{63}^{Inc} = 0.079$, $W_{64}^{Inc} = 0.081$, $W_{65}^{Inc} = 0.081$, $W_{66}^{Inc} = 0.080$, $W_{67}^{Inc} = 0.081$, $W_{68}^{Inc} = 0.080$, $W_{69}^{Inc} = 0.031$, $W_{610}^{Inc} = 0.041$, $W_{611}^{Inc} = 0.047$, $W_{612}^{Inc} = 0.050$, $W_{613}^{Inc} = 0.031$, $W_{614}^{Inc} = 0.038$, $W_{615}^{Inc} = 0.118$, $W_{616}^{Inc} = 0.120$, $W_{617}^{Inc} = 0.120$, $W_{71}^{Inc} = 0.069$, $W_{72}^{Inc} = 0.079$, $W_{73}^{Inc} = 0.079$, $W_{74}^{Inc} = 0.081$, $W_{75}^{Inc} = 0.081$, $W_{76}^{Inc} = 0.080$, $W_{77}^{Inc} = 0.081$, $W_{78}^{Inc} = 0.080$, $W_{79}^{Inc} = 0.109$, $W_{710}^{Inc} = 0.113$, $W_{711}^{Inc} = 0.106$, $W_{712}^{Inc} = 0.113$, $W_{713}^{Inc} = 0.109$, $W_{714}^{Inc} = 0.106$, $W_{715}^{Inc} = 0.052$, $W_{716}^{Inc} = 0.053$, $W_{717}^{Inc} = 0.053$, $W_{81}^{Inc} = 0.069$, $W_{82}^{Inc} = 0.079$, $W_{83}^{Inc} = 0.079$, $W_{84}^{Inc} = 0.081$, $W_{85}^{Inc} = 0.081$, $W_{86}^{Inc} = 0.080$, $W_{87}^{Inc} = 0.081$, $W_{88}^{Inc} = 0.080$, $W_{89}^{Inc} = 0.039$, $W_{810}^{Inc} = 0.023$, $W_{811}^{Inc} = 0.038$, $W_{812}^{Inc} = 0.032$, $W_{813}^{Inc} = 0.048$, $W_{814}^{Inc} = 0.047$, $W_{815}^{Inc} = 0.043$, $W_{816}^{Inc} = 0.053$, $W_{817}^{Inc} = 0.033$, $W_{91}^{Inc} = 0.042$, $W_{92}^{Inc} = 0.143$, $W_{93}^{Inc} = 0.130$, $W_{94}^{Inc} = 0.146$, $W_{95}^{Inc} = 0.134$, $W_{96}^{Inc} = 0.145$, $W_{97}^{Inc} = 0.127$, $W_{98}^{Inc} = 0.145$, $W_{99}^{Inc} = 0.162$, $W_{910}^{Inc} = 0.186$, $W_{911}^{Inc} = 0.166$, $W_{912}^{Inc} = 0.176$, $W_{913}^{Inc} = 0.179$, $W_{914}^{Inc} = 0.183$, $W_{915}^{Inc} = 0.204$, $W_{916}^{Inc} = 0.206$, $W_{917}^{Inc} = 0.206$, $W_{101}^{Inc} = 0.040$, $W_{102}^{Inc} = 0.137$, $W_{103}^{Inc} = 0.143$, $W_{104}^{Inc} = 0.139$, $W_{105}^{Inc} = 0.127$, $W_{106}^{Inc} = 0.132$, $W_{107}^{Inc} = 0.134$, $W_{108}^{Inc} = 0.125$, $W_{109}^{Inc} = 0.109$, $W_{1010}^{Inc} = 0.113$, $W_{1011}^{Inc} = 0.106$, $W_{1012}^{Inc} = 0.113$, $W_{1013}^{Inc} = 0.109$, $W_{1014}^{Inc} = 0.106$, $W_{1015}^{Inc} = 0.185$, $W_{1016}^{Inc} = 0.196$, $W_{1017}^{Inc} = 0.206$, $W_{111}^{Inc} = 0.042$, $W_{112}^{Inc} = 0.130$, $W_{113}^{Inc} = 0.130$, $W_{114}^{Inc} = 0.133$, $W_{115}^{Inc} = 0.134$, $W_{116}^{Inc} = 0.132$, $W_{117}^{Inc} = 0.127$, $W_{118}^{Inc} = 0.132$, $W_{119}^{Inc} = 0.197$, $W_{1110}^{Inc} = 0.176$, $W_{1111}^{Inc} = 0.191$, $W_{1112}^{Inc} = 0.195$, $W_{1113}^{Inc} = 0.197$, $W_{1114}^{Inc} = 0.183$, $W_{1115}^{Inc} = 0.043$, $W_{1116}^{Inc} = 0.033$ and $W_{1117}^{Inc} = 0.033$ as shown in Fig. 5. The priority preferences of suppliers with respect to SKPIs are as follows:

for Price: $SI_1 = SI_5 > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_4 = SI_9 = SI_{11} > SI_{10}$; for Quality: $SI_9 > SI_{10} > SI_{11} = SI_4 > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_1 > SI_5$; for Delivery: $SI_{10} > SI_{11} = SI_9 = SI_4 > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_1 > SI_5$; for Technical capability: $SI_9 > SI_{10} > SI_{11} > SI_4 > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_5 > SI_1$; for Flexibility: $SI_4 > SI_9 = SI_{11} > SI_{10} > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_1 > SI_5$; for Financial position: $SI_9 > SI_4 > SI_{11} = SI_{10} > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_5 > SI_1$; for Geographical location: $SI_4 > SI_{10} > SI_{11} = SI_9 > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_1 > SI_5$; for Market Reputation: $SI_9 > SI_4 > SI_{11} > SI_{10} > SI_2 = SI_3 = SI_6 = SI_7 = SI_8 > SI_5 > SI_1$; for Pollution production: $SI_{11} > SI_9 > SI_{10} = SI_7 = SI_4 = SI_3 > SI_1 > SI_2 > SI_8 > SI_6 > SI_5$; for Pollution control: $SI_9 > SI_{11} > SI_{10} = SI_4 = SI_3 = SI_7 > SI_2 > SI_5 = SI_6 > SI_1 > SI_8$; for Resource consumption:: $SI_{11} > SI_9 > SI_{10} = SI_7 = SI_4 = SI_3 > SI_1 = SI_2 = SI_6 > SI_8 = SI_5$; for Environmental management system: $SI_{11} > SI_9 > SI_{10} = SI_7 = SI_4 = SI_3 > SI_6 > SI_2 > SI_5 = SI_8 > SI_1$; for Green competencies: $SI_{11} > SI_9 > SI_{10} = SI_7 = SI_4 = SI_3 > SI_8 > SI_2 = SI_1 > SI_6 = SI_5$; for Green innovativeness:

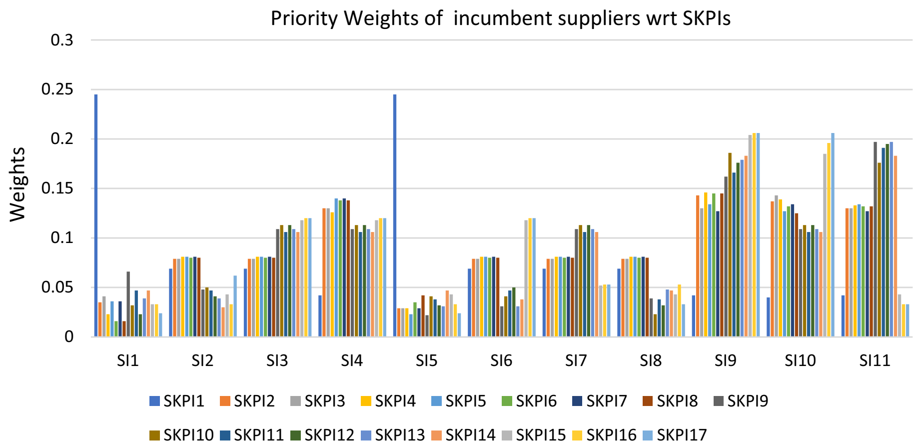


Fig. 5 Priority weights of incumbent supplier with respect to each SKPI

$SI_{11} = SI_9 > SI_{10} = SI_7 = SI_4 = SI_3 > SI_1 = SI_5 = SI_8 > SI_6 > SI_2$; for Safety and health: $SI_9 > SI_{10} > SI_6 = SI_4 = SI_3 > SI_7 > SI_5 = SI_2 = SI_8 = SI_{11} > SI_1$; for The interests and rights of employees: $SI_9 > SI_{10} > SI_6 = SI_4 = SI_3 > SI_7 = SI_8 > SI_1 = SI_2 = SI_5 = SI_{11}$; and for The right of stakeholders:: $SI_9 = SI_{10} > SI_6 = SI_4 = SI_3 > SI_2 > SI_7 > SI_8 = SI_{11} > SI_5 = SI_1$.

Further, the priority weights of incumbent and new suppliers with respect to SKPIs are computed by using the steps of the MARCOS method as explained in Sect. 4.1.1.1.2. The priority weights of incumbent suppliers, $W_1^{Inc} = 0.036$, $W_2^{Inc} = 0.071$, $W_3^{Inc} = 0.087$, $W_4^{Inc} = 0.127$, $W_5^{Inc} = 0.033$, $W_6^{Inc} = 0.075$, $W_7^{Inc} = 0.084$, $W_8^{Inc} = 0.070$, $W_9^{Inc} = 0.147$, $W_{10}^{Inc} = 0.134$ and $W_{11}^{Inc} = 0.135$ as well as the priority weights of new suppliers $W_1^{New} = 0.291$, $W_2^{New} = 0.120$, $W_3^{New} = 0.254$, $W_4^{New} = 0.120$ and $W_5^{New} = 0.215$, are shown in Figs. 6 and Fig. 7 respectively. The incumbent suppliers and new suppliers are arranged in descending order as per their priority weights are as follows: $SI_9 > SI_{11} > SI_{10} > SI_4 > SI_3 > SI_7 > SI_6 > SI_2 > SI_8 > SI_1 > SI_5$ and $SN_1 > SN_3 > SN_5 > SN_4 > SN_2$, respectively.

These weights are utilized in the optimization model as developed in the next section.

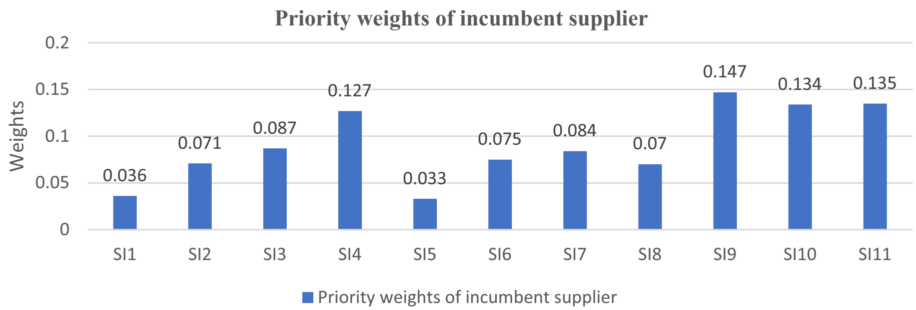
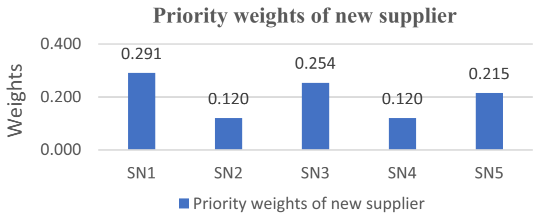


Fig. 6 Priority weights of incumbent supplier using MARCOS

Fig. 7 Priority weights of new supplier using MARCOS



6.3 Stage 3: Development of optimization model

In this section, the applicability of the developed optimization model is discussed through the case problem of the Indian home appliances manufacturing company. The data for the study is given as follows:

This data is associated with 11 incumbent suppliers, 5 new suppliers, 17 SKPIs, and 3 development stages (Advance development, Moderate development, and Primary Development) (Tables 2, 3).

6.4 Stage 4: Solution of optimization model using Fuzzy Epsilon-constraint method.

After data collection, the optimization model is tested. In this study, combined ε-constraint method and max–min fuzzy method is adopted for determining the best compromise solution between the conflicting objectives.

Initially, the payoff table is calculated by determining the individual optima of both objective functions with the help of lexicographic optimization. Here, Lingo 11 optimization software is used to produce the payoff table as shown in Table 4.

The minimum (Rs. 590,000) and maximum (Rs. 621,200) values of first objective function are computed by solving the first objective function (minimization of cost). Similarly, the minimum (14.39) and maximum (16.02) values of second objective function are computed by solving the second objective function (maximization of sustainable performance).

The proposed multi-objective model is solved by ε-constraint method. Further, 'minimization of cost (Z_1)' objective function is considered as the main objective function and 'maximization of sustainable performance (Z_2)' is treated as secondary objective function as per the company's requirements. In summary, the best compromised solution is determined by satisfying both Z_1 and Z_2 objectives using max–min fuzzy method and highlighted in Table 5.

As the model seeks to minimize the cost and maximize the sustainable performance, the best compromised solution (highlighted in "Appendix B" (see Table 5)) is obtained: $Z_1 =$ 605,000 (Rs.) and $Z_2 =$ 15.18. A detailed discussion on obtained results is done in Sect. 6.

7 Discussion

To understand the effectiveness of the proposed integrated MCDM model, the detailed discussion on the outputs of MCDM stages (Stages II and IV) is necessary. To begin with, an understanding of supplier evaluation process can help in determining the priority of suppliers; further, an understanding of the conflicting objective functions can help in choosing the best suited sourcing strategy for supplier, development areas for retrained incumbent suppliers, and investment planning for sourcing strategies. The discussion on output of Stages II and IV is below.

Table 2 The development cost of each development stage for each incumbent supplier with respect to each SKPI (C_{iuv}^{Devlop})

Incumbent Supplier *(i)*	Development Stage *(v)*	Sustainable Key Performance Indicator *(u)*																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Development Cost (Rs.)																
1	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
2	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
3	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
4	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
5	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
6	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
7	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000

Table 2 (continued)

Incumbent Supplier (*i*)	Development Stage (*v*)	Sustainable Key Performance Indicator (*u*)																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Development Cost (Rs.)																
8	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
9	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
10	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000
11	1	20,000	5000	6000	8000	4000	30,000	40,000	50,000	5000	5000	50,000	6000	40,000	6000	5000	4000	5000
	2	15,000	4000	5000	7000	3000	25,000	35,000	45,000	4000	4000	45,000	5000	35,000	5000	4000	3000	4000
	3	10,000	3000	4000	6000	2000	20,000	30,000	40,000	3000	3000	40,000	4000	30,000	4000	3000	2000	3000

Table 3 Financial loss due to switching (C_j^{Switch}), Cost of reducing per unit risk of switching (C_j^{Risk}) and risk of building new relationship with new supplier (R_j^{New})

New Supplier *(j)*	Financial loss due to switching (Rs.)	Cost of reducing per unit risk of switching (Rs.)	Risk of building new relationship
1	40,000	4000	5.6
2	25,000	4000	4.2
3	30,000	4000	3.8
4	35,000	4000	2.0
5	20,000	4000	8.5

$Wbreak_u = 0.3333$, $W_{THu} = 0.07$, $N^{Total} = 11$, $R = 35$, $n'_T = 7$

Table 4 Payoff table

	Z_1	Z_2
Min Z_1	590,000	14.39
Max Z_2	621,200	16.02

7.1 Analysis on SKPIs

It can be seen clearly from Fig. 3, economic category ($w^{Eco} = 0.731$) is the most important SKPI category. The environmental category ($w^{Env} = 0.203$) is next, and the social category ($w^{Soc} = 0.065$) is the least important. Hence, the contributions of economic category are the most vital among the three categories. Aligned with the results found in Fig. 3, Khan et al. (2018) supported the results in their study and concluded that economic performance dimension is an imperative category that requires highest attention when the main objective of company is to become sustainable. This indicates that the economic category of sustainability can help to achieve sustainability goals of manufacturing company in the supplier selection process. This may mean that the performance of environmental and social categories can be attained, if the essential focus of sustainability relies on economic dimensions for supplier selection decisions (Kusi-Sarpong et al., 2019).

From Fig. 2, the results show that the most important SKPI for supplier performance evaluation are Quality ($w_2^{Eco} = 0.312$), Environmental management system ($w_4^{Env} = 0.402$), and Safety and health ($w_1^{Soc} = 0.631$) within economic, environmental, and social categories, respectively. This states that more efforts need to be put on these top ranked SKPIs for improving the contributions of all categories to overall sustainability.

Figure 4 represents the global weight of SKPIs. The top eight ranked SKPIs, within all three categories of sustainability that measure the supplier's sustainability performance, are Quality ($w_2^{SKPI} = 0.228$), Delivery ($w_3^{SKPI} = 0.170$), Price ($w_1^{SKPI} = 0.092$), Environmental management system ($w_{12}^{SKPI} = 0.082$), Technical capability ($w_4^{SKPI} = 0.075$), Flexibility ($w_5^{SKPI} = 0.058$), Pollution control ($w_{10}^{SKPI} = 0.041$), and Safety and health ($w_{15}^{SKPI} = 0.041$). Among these eight top SKPIs, five are from the economic category SKPI, which confirms that an economic-centric focus is essential for achieving supplier sustainability (Lutra et al., 2017). Two environmental category SKPIs affirm that the manufacturing company has emerging concerns towards environmental sustainability for its suppliers (Zimmer et al., 2016). The one social category SKPI assures that social sustainability is vital for measuring and achieving supplier's sustainability performance (Jain & Singh, 2020).

7.2 Analysis on suppliers' sustainable performance

After understanding the priority of SKPIs as per the requirement of the case company, the performance of supplier on these SKPIs is analyzed using MARCOS method. Figure 5 clearly demonstrates that the priority of suppliers with respect to SKPIs are as follows:

Suppliers SI_1 and SI_5 are the best performer and supplier SI_{10} is the worst performer in 'Price' SKPI. Supplier SI_9 performs strongly and supplier SI_5 performs poorly in 'Quality' SKPI. For 'Delivery' SKPI, the best performer and worst performer are supplier SI_{10} and supplier SI_5 respectively. The performance of Supplier SI_9 is best whereas the performance of Supplier SI_1 is bad in 'Technical capability' SKPI. For 'Financial position' SKPI, Supplier SI_9's performance is superior and Supplier SI_1's performance is inferior. Supplier SI_4 exhibits great performance and supplier SI_5 shows poor performance in terms of the 'Geographical location' SKPI. Supplier SI_9 is the best performer and supplier SI_1 is the worst performer in 'Market Reputation' SKPI. Supplier SI_{11} is a great performer and supplier SI_5 is a poor performer in 'Pollution production' SKPI. For 'Pollution control' SKPI, the best performer and worst performer are supplier SI_9 and supplier SI_8 respectively. The performance of Supplier SI_{11} is best whereas the performance of Supplier SI_5 is bad in 'Resource consumption' SKPI. For 'Environmental management system' SKPI, Supplier SI_{11}'s performance is superior and Supplier SI_1's performance is inferior. Supplier SI_{11} is performing great and supplier SI_5 is performing poor in 'Green competencies' SKPI. The performance of Supplier SI_{11} is best whereas the performance of Supplier SI_2 is bad in 'Green innovativeness' SKPI. For 'Safety and health' SKPI, Supplier SI_9 is performing great and supplier SI_1 is performing poor. Supplier SI_9 is the best performer and supplier SI_{11} is the worst performer in 'The interests and rights of employees' SKPI. Supplier SI_9 is performing great and supplier SI_1 is performing poor in 'The right of stakeholders' SKPI.

Further, from Figs. 6 and 7, the priorities of companies towards their incumbent suppliers and new suppliers are clear. Incumbent supplier SI_9 has the best sustainable performance and Incumbent supplier SI_5 has the worst sustainable performance. In the set of new suppliers, company's first choice is SN_1 and last choice is SN_2. But the selection of suppliers can not be done only as per company's preference as company has conflicting objectives and many constraints. Hence, the results are determined with the help of an optimization model.

7.3 Analysis on optimization model results

It is difficult to ascertain which supplier is more important and needs to be selected as well as which of the sourcing strategies is most appropriate for suppliers, but the development of optimization model and its solution through Epsilon constraint method and min–max fuzzy method makes the supplier evaluation and selection process more relevant and analytical.

As the model seeks to minimize the cost and maximize the sustainable performance, the best compromised solution (highlighted in Table 5) is obtained: Z_1= 605,000 (Rs.) and Z_2= 15.18.

This indicates that the minimum total cost is 605000 (Rs.) and the maximum value of sustainable performance of supplier is 15.18. The results indicates that company can continue procurement from their incumbent suppliers SI_2, SI_3, SI_4, SI_6, SI_7, SI_9, SI_{10} and SI_{11} but they require assistance for their development. This finding also stands that the development cost is less than the switching cost for these retained incumbent suppliers. As model focuses on determining the development area, Supplier SI_2 requires advance development for Quality, Delivery—advance development, Technical capability, Flexibility, Pollution production, Pollution control, Environmental management system, Green innovativeness, Safety and health, The interests and rights of employees, and The rights of stakeholders. The development stage for Supplier SI_3 with respect to each SKPI is Quality- advance development, Delivery—advance development, Technical capability—advance development, Flexibility—advance development, Pollution production—advance development, Pollution control—advance development, Environmental management system—advance development, Green innovativeness—advance development, Safety and health—advance development, The interests and rights of employees—advance development, The rights of stakeholders—advance development. Supplier SI_4 belongs to advance development stage for Quality, Delivery—advance development, Technical capability, Flexibility, Pollution production, Pollution control, Environmental management system, Green innovativeness, Safety and health, The interests and rights of employees, and The rights of stakeholders. For supplier SI_6, the development stage for each SKPI is Quality—advance development, Delivery—advance development, Technical capability—advance development, Flexibility—advance development, Pollution production—advance development, Pollution control—advance development, Environmental management system—advance development, Green innovativeness—advance development, Safety and health—advance development, The interests and rights of employees—advance development, The rights of stakeholders—advance development. Supplier SI_7 belongs to advance development stage for Quality, Delivery—advance development, Technical capability, Flexibility, Pollution production, Pollution control, Environmental management system, Green innovativeness, Safety and health, The interests and rights of employees, and The rights of stakeholders. Supplier SI_9 requires advance development for Quality, Delivery—advance development, Technical capability, Flexibility, Pollution production, Pollution control, Environmental management system, Green innovativeness, Safety and health, The interests and rights of employees, and The rights of stakeholders. Supplier SI_{10} comes under advance development stage for all development SKPIs. For supplier SI_{11}, the development stage for each SKPI is Quality—advance development, Delivery—advance development, Technical capability—advance development, Flexibility—advance development, Pollution production—advance development, Pollution control—advance development, Environmental management system—advance development, Green innovativeness—advance development, Safety and health—advance development, The interests and rights of employees—advance development, The rights of stakeholders—advance development.

For the remaining existing suppliers (SI_1, SI_5, and SI_8), the development cost is higher than the switching cost. Hence, company need to switch suppliers SI_1, $SI_{5,}$ and SI_8 and replace them with new suppliers SN_2, SN_3, and SN_5.

In summary, the above discussion confirms that the proposed integrated MCDM model is well suited for home appliance manufacturing companies in Indian context.

8 Managerial Implications

In the current study, the proposed integrated MCDM model highlights useful managerial implications for practitioners and academicians. The decision variables help the company to evaluate supplier sustainable performance, choose an appropriate sourcing strategy for each supplier, and determine vital development areas of incumbent suppliers. This awareness will help the company to improve their sustainability degree through their supply chain partner (supplier). This proposed integrated MCDM model addresses the various issues of supplier selection process and allows the experts of company and suppliers to think analytically and deeply. As results demonstrate, this proposed integrated MCDM model provides clarity to suppliers regarding most important SKPIs so that they can try to improve their sustainable performance. Based on the results of stage 2, companies might have clear vision towards priorities of their suppliers, and they can measure it. From the output of stage 4, companies may confidently decide which supplier needs to be switched or developed. In some cases, it might be more profitable to choose supplier switching option and, in some cases, supplier development option might be more profitable. This study may help the companies to choose the most efficient sourcing strategy for their suppliers from the perspective of sustainability.

The conclusion of this study is that companies can assess their suppliers based on their sustainable requirement that will help them to improve their performance by utilizing stage 1 and stage 2 of the proposed integrated MCDM model, whereas stage 3 and stage 4 can help companies to choose appropriate sourcing strategies for their supplier while maintaining the tradeoff between cost and sustainable performance.

9 Conclusion

In this study, a novel integrated MCDM model is proposed to efficiently evaluate sustainable supplier selection and appropriate sourcing strategy selection. This model consists of four stages. In the first stage, SKPIs for evaluating supplier in the view of sustainability are identified. BWM method is utilized to compute the priority weights of SKPIs, and MARCOS method is utilized to compute the priority weights of suppliers in the second stage. Stage 3 proposes a bi-objective mathematical model for selecting the optimum sourcing strategies and suppliers as well as investment cost for each supplier based on the evaluation weights of incumbent and new suppliers while optimizing cost and sustainable performance. The solution approach (Epsilon constraint method and min–max fuzzy method), in the fourth stage, is utilized to provide optimal solutions of mathematical model. The numerical implementation of the proposed model is presented for a case company that aids experts to select suppliers and their respective sourcing strategies as well as find the development areas of retained incumbent suppliers.

There are some limitations that may lead to interesting future research directions. First, a small size problem has been considered in this study and an optimization solver is utilized to solve the bi-objective mathematical model in coherent computational time. Since the considered data set is quite small, this model can be extended for a large data set. This could be a future research direction for researchers. Second, for a larger data set, the utilized approach may not be sufficient. Heuristic approaches can be explored to determine the solutions. Third, since the supplier performance indicators in this study are identified for the home appliances manufacturing company, these indicators might not be relevant for all sectors/industries. Therefore, different dimensions can be explored for sustainable supplier selection problems in different sectors/industries. Fourth, the model considered only a single product of home appliances. However, it can be extended for other home appliance products easily. Fifth, our optimization model is validated only for specified case study and its mathematical formulation is developed under general notations, parameters, and variables. This model can be applicable for other case studies. Finally, order allocation and vehicle routing problems can be included in the proposed model for future research direction. In addition, exploring the impact of various industry 4.0 technologies (Matthess et al., 2022; Govindan, et al., 2022a; Govindan, 2022a, 2022b; Govindan et al., 2022c) on sustainable supplier selection could be an interesting future research direction.

Appendix A

A.1 Multi-criteria decision making (MCDM)

MCDM is the study of methods that are applied to make decisions in the presence of multiple, usually conflicting, criteria (Törn, 1980). MCDM has become a powerful tool to solve design problems that involve multiple conflicting quantitative and qualitative criteria. It includes different perspectives and varied knowledge domains of the decision makers (DMs) so that all the criteria are properly catered for optimizing the problem and attaining appropriate decisions as per the objective (Mousavi-Nasab, and Sotoudeh-Anvari, 2017). Hence, MCDM methods are best utilized in situations where conjoint decision analysis is required and the conflicts among conjoint DMs are needed to transform into priority weights (Chowdhury & Paul, 2020). Ching and Kwangsun (1981) have classified the problems of MCDM broadly into two categories: 1) Multiple Attribute Decision Making (MADM), 2) Multiple Objective Decision Making (MODM). The aim of the study is to utilize the combined efficiencies and effectiveness of both MODM and MADM. The combined approach is extremely beneficial in decision making problem situations that include the multi-dimensions of sustainability objectives. It facilitates an efficient framework to model the complexities while formulating the supply chain problems and enables DMs for participating actively in decision making. The key concepts of MODM and MADM techniques used in the study are briefly described below.

A.1.1 Multiple attribute decision making (MADM)

MADM methods are applied to evaluate and solve discrete problems with limited number of predetermined alternatives (Zavadskas & Turskis, 2011). Evaluating a limited number of alternatives inherent in a range of attributes is difficult; prioritizing them adds further complexity. To solve such arrays of problems, MADM methods are best suited. In MADM, the final selection of the alternative is decided by various alternatives' comparisons with respect to each inter- and intra-attribute. The comparisons may include explicit or implicit tradeoffs. The MADM methods BWM and MARCOS applied in this study to evaluate the supplier performance are explained briefly below while we provide the advantages of both over other MADM methods.

A.1.1.1 Best–worst method The best worst method (BWM) is a MADM method that has been proposed by Rezaei (2015). BWM is based on pairwise comparisons; the advantages of this method over other MCDM methods are: 1) it requires less pairwise comparison data entries as compared to other full pairwise comparison based MADM methods, and 2) the consistency of results generated from BWM are better than the other full pairwise comparison-based MADM methods. Given the above advantages of BWM, it has become a popular MADM technique and is extremely useful in various applications such as supplier selection (Rezaei et al., 2016), social sustainability assessment of supply chains (Ahmadi et al., 2017), sustainable Manufacturing (Malek & Desai, 2021), R&D performance evaluation of firms (Salimi & Rezaei, 2018), facility location selection (Kheybari et al., 2019), sustainable manufacturing barriers prioritization (Malek & Desai, 2019), risk analysis (Yazdi et al., 2020), and Lean six sigma enablers prioritization (Singh et al., 2021).

As discussed previously, a set of SKPIs $\{SKPI_1, SKPI_2, \ldots, SKPI_U\}$ are divided into three categories. The sets of economic, environmental, and social sub-SKPIs $\{SKPI_1^{Eco}, SKPI_2^{Eco}, \ldots, SKPI_L^{Eco}\}$, $\{SKPI_1^{Env}, SKPI_2^{Env}, \ldots, SKPI_M^{Env}\}$, and $\{SKPI_1^{Soc}, SKPI_2^{Soc}, \ldots, SKPI_N^{Soc}\}$ respectively are chosen for sustainable evaluation of suppliers. The steps of BWM for finding the importance of ranking of SKPIs are structured as follows:

Step 1: Determine the best and worst SKPI:

The best economic $SKPI^{Eco}$ $\left(SKPI_B^{Eco}, B \in \{1, 2, \ldots, L\}\right)$ i.e., the most important economic SKPI and the worst economic $SKPI^{Eco}$ $(SKPI_W^{Eco}, W \in \{1, 2, \ldots, L\}))$ i.e., the least important economic SKPI are identified by each of the k DMs.

Step 2: Compute the preference of $SKPI_B^{Eco}$, over all the other SKPIs:

Using a scale of 1–9, the preference of $SKPI_B^{Eco}$ over each $SKPI_h^{Eco}$ is calculated for kth DM, denoted as $a_{Bh}^k \text{with} a_{BB}^k = 1$. This results in the best-to-others (BO) vector $A_B^k = (a_{B1}^k, a_{B2}^k, \ldots, a_{BL}^k)$

Step 3: Compute the preference of $SKPI_W^{Eco}$ over all the other SKPIs:

Using the same scale, the preference of each $SKPI_h^{Eco}$ over worst KPI $SKPI_W^{Eco}$ is calculated for kth DM, denoted as $a_{hW}^k \text{with} a_{WW}^k = 1$. This results in the others-to-worst (OW) vector $A_W^k = (a_{1W}^k, a_{2W}^k, \ldots, a_{LW}^k)$

Step 4: Calculate the optimal weights of each $SKPI^{Eco}$ for each DM.

To determine the unique optimal weighting vector $\left(w_1^{k*}, w_2^{k*}, \ldots, w_L^{k*}\right)$ of the set of SKPIs for kth DM, the following maximum absolute difference is to be minimized:

$$max\left\{\left|w_B^{k*} - a_{Bl}^k w_l^{k*}\right|, \left|w_l^{k*} - a_{lW}^k w_W^{k*}\right|; l = 1, 2, \ldots, L\right\}$$

This is achieved by the following optimization model:

$$\begin{aligned}
& min \max_l \{|\frac{w_B^{k*}}{w_l^{k*}} - a_{Bl}^k|, |\frac{w_l^{k*}}{w_W^{k*}} - a_{lW}^k|\} \\
& \text{Subject to} \\
& \sum_l w_l^{k*} = 1 \\
& w_l^{k*} \geq 0, \quad \forall l \in \{1, 2, \ldots, L\}
\end{aligned} \tag{P1}$$

The above fractional programming problem formulation (P1) is transformed into a linear programming problem formulation as given below (Rezaei, 2016):

$$\begin{aligned}
& \min \xi^k \\
& \text{Subject to} \\
& \left|w_B^k - a_{Bl}^k w_l^k\right|\} \leq \xi^k \quad \forall l \in \{1, 2, \ldots, L\} \\
& \left|w_l^k - a_{lW}^k w_W^k\right|\} \leq \xi^k \quad \forall l \in \{1, 2, \ldots, L\} \\
& \sum_l w_l^k = 1 \\
& w_l^k \geq 0, \quad \forall l \in \{1, 2, \ldots, L\}
\end{aligned} \tag{P2}$$

Problem (P2) provides a unique optimal weighting vector $\left(w_1^{k*}, w_2^{k*}, \ldots, w_L^{k*}\right)$ and optimal value ξ^{k*} for kth DM. The desirable value of ξ^{k*} is closer to zero as it indicates a high consistency and high reliability.

Problem (P2) is solved to compute the optimal weighting vector for each DM. Further, for computing the final weights of each $SKPI^{Eco}$, the average of all the attained optimal weights for DMs is calculated by given formula.

$$w_l^{Eco} = \frac{\sum_{k=1}^{K} w_l^{k*}}{K} \quad \forall l = 1, 2, \ldots, L. \tag{11}$$

The final optimal weighting vector $(w_1^{Eco}, w_2^{Eco}, \ldots, w_L^{Eco})$ is determined and provides the priority weights of each $SKPI^{Eco}$. Similarly, this procedure is performed for $SKPI^{Env}$ and $SKPI^{Soc}$ to determine the optimal weighting vectors $(w_1^{Env}, w_2^{Env}, \ldots, w_M^{Env})$ and $(w_1^{Soc}, w_2^{Soc}, \ldots, w_N^{Soc})$ respectively.

Further, the procedure is repeated for three categories (economic, environmental, and social) and determines the optimal weighting vector $\left(w^{Eco}, w^{Env}, w^{Soc}\right)$.

To compute the global weights of each SKPI $w_1^{SKPI}, w_2^{SKPI}, \ldots, w_U^{SKPI}$, the weight obtained for each SKPI belong to each category is multiplied by the weight of the category.

A.1.1.2 MARCOS Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) is a MADM technique developed by Stevic, Pamučar, Puška, and Chatterjee (2020). The main advantage of this method over other MADM methods is its consideration of ideal and anti-ideal alternatives at the initial stage of the evaluation process. The closer determination of utility degree with respect to ideal and anti-ideal solutions provides greater stability while considering a large set of criteria and alternatives. The steps of the MARCOS method for computing the priority weights of incumbent and new suppliers with respect to SKPIs are described as follows:

Step 1: Develop an initial decision-making matrix

In this step, a decision matrix is developed for incumbent suppliers with respect to each DM. The opinions of all DMs are included to form a decision matrix for supplier evaluation with respect to SKPIs. DMs are asked to evaluate the U SKPIs for each incumbent supplier on the scale of five degrees: 1,3,5,7 and 9, where 1 = very poor, 3 = poor, 5 = average, 7 = good, 9 = very good. The evaluation decision matrix filled by kth DM is

$$T^k = \begin{bmatrix} x_{11}^k & x_{12}^k & \cdots & x_{1U}^k \\ x_{21}^k & x_{22}^k & \cdots & x_{2U}^k \\ \cdots & \cdots & \cdots & \cdots \\ x_{I1}^k & x_{I2}^k & \cdots & x_{IU}^k \end{bmatrix} \tag{12}$$

In group decision-making, evaluation decision matrices formed by members of expert panel are aggregated into initial decision-making matrix by taking the average of evaluation decision matrices. The initial decision-making matrix is

$$T = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1U} \\ x_{21} & x_{22} & \cdots & x_{2U} \\ \cdots & \cdots & \cdots & \cdots \\ x_{I1} & x_{I2} & \cdots & x_{IU} \end{bmatrix} \tag{13}$$

Step 2: Form an extended initial matrix

To extend the initial decision-making matrix, the ideal (AI) and anti-ideal (AAI) solutions are computed. The AI solution is the best incumbent supplier with respect to SKPIs, whereas the AAI solution is the worst incumbent supplier with respect to SKPIs. Based on the nature of the SKPIs, AI and AAI are defined as follows:

$$AI = \max_i x_{iu} \; if \; u \epsilon Ben \; and \; \min_i x_{iu} \; if \; u \epsilon Cos \tag{14}$$

$$AAI = \min_i x_{iu} \; if \; u \epsilon Ben \; and \; \max_i x_{iu} \; if \; u \epsilon Cos \tag{15}$$

where Ben: a benefit group of SKPIs, and Cos: a group of cost SKPIs.

The extended initial matrix X is performed as follows:

$$X = \begin{array}{c} \\ AAI \\ SI_1 \\ SI_2 \\ \cdots \\ SI_I \\ AI \end{array} \begin{array}{c} \begin{array}{cccc} SKPI_1 & SKPI_2 & \ldots & SKPI_U \end{array} \\ \begin{bmatrix} x_{aa1} & x_{aa2} & \cdots & x_{aaU} \\ x_{11} & x_{12} & \cdots & x_{1U} \\ x_{21} & x_{22} & \cdots & x_{2U} \\ \cdots & \cdots & \cdots & \cdots \\ x_{I1} & x_{I2} & \cdots & x_{IU} \\ x_{ai1} & x_{ai2} & \cdots & x_{aiU} \end{bmatrix} \end{array} \tag{16}$$

Step 3: Normalize the extended initial matrix

The extended initial matrix X is normalized to obtain normalized extended initial matrix $Y = [y_{iu}]_{I \times U}$ by using the following equations:

$$y_{iu} = \frac{x_{ai}}{x_{iu}} \; if \; u \epsilon \text{Cos} \tag{17}$$

$$y_{iu} = \frac{x_{iu}}{x_{ai}} \; if \; u \epsilon Ben \tag{18}$$

where x_{ai} and x_{iu} are the elements from the initial decision matrix.

Step 4: Determine the weighted matrix

The weighted matrix $Z = [z_{iu}]_{I \times U}$ is computed by multiplying the normalized matrix Y with the weight coefficient of the SKPI w_u^{SKPI}, using the following expression:

$$z_{iu} = y_{iu} \times w_u^{SKPI} \tag{19}$$

Step 5: Calculate the utility degree of suppliers

The utility degree of each incumbent supplier with regard to anti-ideal and ideal solution are computed using the following expressions:

$$P_i^- = \frac{Q_i}{Q_{aai}} \tag{20}$$

$$P_i^+ = \frac{Q_i}{Q_{ai}} \tag{21}$$

where Q_i represents the sum of the elements of the weighted matrix Z using following expression:

$$Q_i = \sum_{i=1}^{I} z_{iu} \tag{22}$$

Step 6: Determine the utility function of alternatives

The utility function of each incumbent supplier with regard to the ideal and anti-ideal solution is determined using the following expression:

$$f(P_i) = \frac{P_i^+ + P_i^-}{1 + \frac{1-f(P_i^+)}{f(P_i^+)} + \frac{1-f(P_i^-)}{f(P_i^-)}}; \tag{23}$$

where $f\left(P_i^-\right)$: the utility function with regard to the anti-ideal solution and $f\left(P_i^+\right)$: the utility function with regard to the ideal solution. These are computed by using the following expression:

$$f\left(P_i^-\right) = \frac{P_i^+}{\left(P_i^+ + P_i^-\right)} \tag{24}$$

$$f\left(P_i^+\right) = \frac{P_i^-}{\left(P_i^+ + P_i^-\right)} \tag{25}$$

Step 7: Compute the weightage of alternatives
The priority weights of incumbent suppliers are computed by normalizing the final utility function values. For each incumbent supplier, it is desirable to achieve highest utility function value.

This procedure is repeated for the set of new suppliers to determine their priority weights.

A.1.2 Multiple objective decision making (MODM)

The Multiple objective decision making (MODM) technique is best suited for continuous decision spaces and associated with the problem where the alternatives are non-predetermined (Zavadskas et al., 2014). The aim of considered problem is to design the 'best' alternative under consideration of a set of quantifiable objectives and a set of well-defined designed constraints. MODM facilitates a process of obtaining some tradeoff information, implicit or explicit, between the stated quantifiable objectives and also between stated or unstated nonquantifiable objectives.

Real world decision-making problems generally have multi-objectives that cannot be optimized simultaneously due to inherent incommensurability and conflict between these objectives. Thus, to get the best compromise solution, achievement of trade-off between these objective plays a main role. Several methodologies are proposed for solving MODM problems in the existing literature (Hwang et al., 1993).

Mathematically, MODM problems can be expressed as follows:

$$\min F(x) = [f_1(x), f_2(x), \ldots, f_O(x)]^T$$

s.t.

$$x \epsilon S = \{\ x|g_h(x))\{\geq, =, \leq\}0, h = 1, 2, \ldots, H\}$$

where $S \subseteq R^n$ is the feasible space (Steuer, 1986).

The problem consists of H constraints and O objectives. $f_o(x)$ and $g_h(x)$, can be linear or non-linear.

As discussed earlier, optimization of all the objectives simultaneously is not possible. In this case, the concept of non-inferiority i.e., known as efficiency or Pareto optimality is utilized to obtain the solution to the MODM problems. This concept is based on the following definitions (Hsiao et al., 1994):

Definition 1 The feasible region S is the set of state vectors x that satisfy the constraints: $S = \{\ x|g_h(x))\{\geq, =, \leq\}0, h = 1, 2, \ldots, H\}$.

Definition 2 A point $\check{x}\epsilon S$ is a local non-inferior point if there exists an $\rho > 0$ such that in the neighborhood $N(\check{x}, \rho)$ of $\check{x}$, there exists no other point x such that (i) $f_o(x) \leq f_o(\check{x}), o = 1, 2, \ldots, O$ and (ii) $f_{o'}(x) < f_{o'}(\check{x})$, for some $o'\epsilon\{1, 2, \ldots, O'\}$.

Definition 3 A point $\check{x}\epsilon S$ is a global non-inferior point if and only if there exists no other point x such that (i) $f_o(x) \leq f_o(\check{x}), i = 1, 2, \ldots, O$ and (ii) $f_{o'}(x) < f_{o'}(\check{x})$, for some $o'\epsilon\{1, 2, \ldots, O'\}$.

A non-inferior solution of a MODM problem is one in which any improvement of one objective function can be achieved only at the expense of at least one of the other objectives. In general, there are an infinite number of (global) non-inferior points for a given MODM problem; this makes the task of finding the collection of such points called the non-inferior set extremely difficult.

For generating an entire non-inferior set, there are few methods such as the weight sum method, kth-objective method, and the Epsilon constraint method. In the current study, the Epsilon constraint method, applied to solve the proposed optimization model, is discussed in detail as follows.

A.1.2.1 Epsilon constraint method The Epsilon constraint is a MODM approach, proposed by Haimes (1971), to generate Pareto optimal solutions. These solutions provide a clear understanding of the Pareto optimal set. In this method, initially the primary objective function and secondary objective functions are decided (Engau & Wiecek, 2007). Further, the MODM problem is transformed into single objective problem by shifting the other objectives in constraints with some allowable amount ε (Nouri et al., 2018). The advantages of ε-constraint method over other MODM methods are such as (i) Weighting approach results in merely Pareto optimal extreme solutions for linear models, whereas non-extreme solutions can be produced through applying ε-constraint method. (ii) Unlike the weighting approach, in multi-objective problems via integer programming as well as mixed-integer linear programming ones, unsupported Pareto optimal solutions can be produced by ε-constraint method. (iii) Weighting approach highly depends on the scaling of objective functions while this issue is not important in the ε-constraint method. (iv) The controlled number of Pareto optimal solutions can be produced in ε-constraint method by effectively tuning the number of grid points in the range of each objective function.

Based on ε-constraint method, a single-objective model of problem (P3) is represented as follows:

$$
\begin{aligned}
&\text{Objective Function} = Min f_1(x)\\
&s.t.\\
&f_o(x) \geq \epsilon_o, o = 2, 3, \ldots, O\\
&x\varepsilon S = \{\ x|g_h(x))\{\geq, =, \leq\}0, h = 1, 2, \ldots, H\}
\end{aligned}
$$

For generating the Pareto optimal solutions, the ε_o are altered from minimum to maximum amount of $f_o(x)$ and the goal is obtained.

A.2 Fuzzy decision

For deciding the best compromised solution, max–min fuzzy method is utilized in this study. This method a fuzzy membership function in the interval [0,1] to each solution in the Pareto front (Cao et al., 2019). The fuzzy membership functions for oth objective function are as follows:

$$\mu_o^r = \begin{cases} 1 & \theta_o^r \le \theta_o^{min} \\ \frac{\theta_o^{max} - \theta_o^r}{\theta_o^{max} - \theta_o^{min}} & \theta_o^{min} \le \theta_o^r \le \theta_o^{max} \\ 0 & \theta_o^r \ge \theta_o^{max} \end{cases} \tag{26}$$

where μ_o^r: the optimality degree of the rth solution of oth objective function.

In the oth objective function f_o^{min} and f_o^{max} are the minimum and maximum values of Pareto solutions. Then, per unit quantities are compared and the minimum value is selected based on Eq. (17). Finally, the best point as trade-off solution for multi-objective solution is the maximum amount of all the minimums Eq. (18).

$$\mu^r = \min(\mu_1^r, \ldots, \mu_o^r); \forall r = 1, 2, \ldots . Rp \tag{27}$$

$$\mu^{max} = \max\left(\mu^1, \mu^2, \ldots, \mu^{Rp}\right). \tag{28}$$

Appendix B

See Table 5.

Table 5 Pareto result solutions

Min Z1	Max Z2	μ1	μ2	Min (μ1, μ2)
590,000	14.390	1.000	0.000	0.000
594,000	14.400	0.872	0.006	0.006
594,000	14.410	0.872	0.012	0.012
594,000	14.420	0.872	0.018	0.018
594,000	14.430	0.872	0.025	0.025
594,000	14.440	0.872	0.031	0.031
594,000	14.450	0.872	0.037	0.037
594,000	14.460	0.872	0.043	0.043
594,000	14.470	0.872	0.049	0.049
594,000	14.480	0.872	0.055	0.055
594,000	14.490	0.872	0.061	0.061
594,000	14.500	0.872	0.068	0.068
594,000	14.510	0.872	0.074	0.074
594,000	14.520	0.872	0.080	0.080
594,000	14.530	0.872	0.086	0.086
594,000	14.540	0.872	0.092	0.092
594,000	14.550	0.872	0.098	0.098

Table 5 (continued)

Min Z1	Max Z2	μ1	μ2	Min (μ1, μ2)
594,000	14.560	0.872	0.104	0.104
594,000	14.570	0.872	0.110	0.110
594,000	14.580	0.872	0.117	0.117
594,000	14.590	0.872	0.123	0.123
594,000	14.600	0.872	0.129	0.129
594,000	14.610	0.872	0.135	0.135
594,000	14.620	0.872	0.141	0.141
594,000	14.630	0.872	0.147	0.147
594,000	14.640	0.872	0.153	0.153
594,000	14.650	0.872	0.160	0.160
594,000	14.660	0.872	0.166	0.166
594,000	14.670	0.872	0.172	0.172
594,000	14.680	0.872	0.178	0.178
594,000	14.690	0.872	0.184	0.184
594,000	14.700	0.872	0.190	0.190
594,000	14.710	0.872	0.196	0.196
594,000	14.720	0.872	0.203	0.203
594,000	14.730	0.872	0.209	0.209
594,000	14.740	0.872	0.215	0.215
594,000	14.750	0.872	0.221	0.221
594,000	14.760	0.872	0.227	0.227
594,000	14.770	0.872	0.233	0.233
594,000	14.780	0.872	0.239	0.239
594,000	14.790	0.872	0.246	0.246
594,000	14.800	0.872	0.252	0.252
594,000	14.810	0.872	0.258	0.258
594,000	14.820	0.872	0.264	0.264
594,000	14.830	0.872	0.270	0.270
594,000	14.840	0.872	0.276	0.276
594,000	14.850	0.872	0.282	0.282
594,000	14.860	0.872	0.289	0.289
594,000	14.870	0.872	0.295	0.295
594,000	14.880	0.872	0.301	0.301
594,000	14.890	0.872	0.307	0.307
594,000	14.900	0.872	0.313	0.313
594,000	14.910	0.872	0.319	0.319
594,000	14.920	0.872	0.325	0.325

Table 5 (continued)

Min Z1	Max Z2	μ1	μ2	Min (μ1, μ2)
594,000	14.930	0.872	0.331	0.331
594,000	14.940	0.872	0.338	0.338
594,000	14.950	0.872	0.344	0.344
594,000	14.960	0.872	0.350	0.350
594,000	14.970	0.872	0.356	0.356
594,000	14.980	0.872	0.362	0.362
594,000	14.990	0.872	0.368	0.368
594,000	15.000	0.872	0.374	0.374
594,000	15.010	0.872	0.381	0.381
594,000	15.020	0.872	0.387	0.387
594,000	15.030	0.872	0.393	0.393
594,000	15.040	0.872	0.399	0.399
594,000	15.050	0.872	0.405	0.405
594,000	15.060	0.872	0.411	0.411
594,000	15.070	0.872	0.417	0.417
594,000	15.080	0.872	0.424	0.424
594,000	15.090	0.872	0.430	0.430
594,000	15.100	0.872	0.436	0.436
594,000	15.110	0.872	0.442	0.442
594,000	15.120	0.872	0.448	0.448
594,000	15.130	0.872	0.454	0.454
594,000	15.140	0.872	0.460	0.460
594,000	15.150	0.872	0.467	0.467
605,000	15.160	0.519	0.473	0.473
605,000	15.170	0.519	0.479	0.479
605,000	**15.180**	**0.519**	**0.485**	**0.485**
606,200	15.190	0.481	0.491	0.481
606,200	15.200	0.481	0.497	0.481
606,200	15.210	0.481	0.503	0.481
606,200	15.220	0.481	0.510	0.481
606,200	15.230	0.481	0.516	0.481
606,200	15.240	0.481	0.522	0.481
606,200	15.250	0.481	0.528	0.481
606,200	15.260	0.481	0.534	0.481
606,800	15.270	0.462	0.540	0.462
606,800	15.280	0.462	0.546	0.462

Table 5 (continued)

Min Z1	Max Z2	μ1	μ2	Min (μ1, μ2)
606,800	15.290	0.462	0.552	0.462
606,800	15.300	0.462	0.559	0.462
606,800	15.310	0.462	0.565	0.462
606,800	15.320	0.462	0.571	0.462
606,800	15.330	0.462	0.577	0.462
606,800	15.340	0.462	0.583	0.462
606,800	15.350	0.462	0.589	0.462
606,800	15.360	0.462	0.595	0.462
606,800	15.370	0.462	0.602	0.462
606,800	15.380	0.462	0.608	0.462
606,800	15.390	0.462	0.614	0.462
606,800	15.400	0.462	0.620	0.462
606,800	15.410	0.462	0.626	0.462
606,800	15.420	0.462	0.632	0.462
606,800	15.430	0.462	0.638	0.462
606,800	15.440	0.462	0.645	0.462
606,800	15.450	0.462	0.651	0.462
606,800	15.460	0.462	0.657	0.462
606,800	15.470	0.462	0.663	0.462
606,800	15.480	0.462	0.669	0.462
606,800	15.490	0.462	0.675	0.462
606,800	15.500	0.462	0.681	0.462
606,800	15.510	0.462	0.688	0.462
606,800	15.520	0.462	0.694	0.462
606,800	15.530	0.462	0.700	0.462
606,800	15.540	0.462	0.706	0.462
606,800	15.550	0.462	0.712	0.462
606,800	15.560	0.462	0.718	0.462
606,800	15.570	0.462	0.724	0.462
606,800	15.580	0.462	0.731	0.462
606,800	15.590	0.462	0.737	0.462
606,800	15.600	0.462	0.743	0.462
606,800	15.610	0.462	0.749	0.462
606,800	15.620	0.462	0.755	0.462
606,800	15.630	0.462	0.761	0.462
606,800	15.640	0.462	0.767	0.462
606,800	15.650	0.462	0.773	0.462
606,800	15.660	0.462	0.780	0.462

Table 5 (continued)

Min Z1	Max Z2	μ1	μ2	Min (μ1, μ2)
606,800	15.670	0.462	0.786	0.462
606,800	15.680	0.462	0.792	0.462
606,800	15.690	0.462	0.798	0.462
606,800	15.700	0.462	0.804	0.462
606,800	15.710	0.462	0.810	0.462
606,800	15.720	0.462	0.816	0.462
606,800	15.730	0.462	0.823	0.462
606,800	15.740	0.462	0.829	0.462
606,800	15.750	0.462	0.835	0.462
606,800	15.760	0.462	0.841	0.462
606,800	15.770	0.462	0.847	0.462
606,800	15.780	0.462	0.853	0.462
606,800	15.790	0.462	0.859	0.462
606,800	15.800	0.462	0.866	0.462
609,000	15.810	0.391	0.872	0.391
609,000	15.820	0.391	0.878	0.391
609,000	15.830	0.391	0.884	0.391
609,000	15.840	0.391	0.890	0.391
609,000	15.850	0.391	0.896	0.391
609,000	15.860	0.391	0.902	0.391
609,000	15.870	0.391	0.909	0.391
609,000	15.880	0.391	0.915	0.391
609,000	15.890	0.391	0.921	0.391
609,000	15.900	0.391	0.927	0.391
610,200	15.910	0.353	0.933	0.353
610,200	15.920	0.353	0.939	0.353
610,200	15.930	0.353	0.945	0.353
610,200	15.940	0.353	0.952	0.353
610,200	15.950	0.353	0.958	0.353
610,200	15.960	0.353	0.964	0.353
610,200	15.970	0.353	0.970	0.353
610,200	15.980	0.353	0.976	0.353
621,200	15.990	0.000	0.982	0.000
621,200	16.000	0.000	0.988	0.000
621,200	16.010	0.000	0.994	0.000
621,200	16.019	0.000	1.000	0.000

Best compromised solution

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