An Integrated Approach of Fuzzy Quality Function Deployment and Fuzzy Multi-Objective Programming to Sustainable Supplier Selection and Order Allocation

Amir Hossein Azadnia [a], Pezhman Ghadimi [b,*]

[a]*Assistant Professoe, Department of Industrial Engineering, Ayatollah Amoli Branch, Islamic Azad University, Amol, Iran*
[b]*Assistant Professor, School of Mechanical and Materials Engineering, University College Dublin, Ireland*

Abstract

The emergence of sustainability paradigm has influenced many research disciplines including supply chain management. It has drawn the attention of manufacturing companies' CEOs to incorporate sustainability in their supply chain and manufacturing activities. Supplier selection problem, as one of the main problems in supply chain activities, is also combined with sustainable development where traditional procedures are now transformed to sustainable initiatives. Moreover, allocating optimal order quantities to sustainable suppliers has also attracted attention of many scholars and industrial practitioners, which has not been comprehensively addressed. Therefore, a practical model of supplier selection and order allocation based on the sustainability Triple Bottom Line (TBL) approach is presented in this research article. The proposed approach utilizes Fuzzy Analytical Hierarchy Process combined with Quality Function Deployment (FAHP-QFD) for reflecting buyer's sustainability requirements into the preference weights that are then exerted by an efficient Fuzzy Assessment Method (FAM) to assess the suppliers to obtain their sustainability scores. Thereupon, these scores are utilized in a fuzzy multi-objective mix-integer non-linear programming model (MINLP) for allocating orders to suppliers based on the manufacturer's sustainability preference. A real-world application of food industry is presented to show the practicality of the proposed approach.

*Keyword*s: Sustainability, Sustainable supplier selection, Fuzzy inference system, Order allocation, Fuzzy multi-objective non-linear programming.

1. Introduction

Natural resource consumption and excessive waste generation that fall in the category of environmental foot print are increasingly turning to be the major concerns of the companies that are trying to either manage their existing supply chains or develop new products and services. To fully understand product sustainability, a business must consider not only its own operations, but also its entire network of suppliers, customers, and supporting resources (Fiksel, 2010). Social and green supplier development is necessary for an effective sustainable supply chain. In addition, the consideration of both environmental and social factors needs to be at the forefront of organizations' supplier selection agenda (Bai and Sarkis, 2010).

Sikdar (2012) stated five major steps for attempting to conduct a sustainable assessment. Firstly, the system that needs to be analysed regarding sustainability perspective must be defined together with the system boundary. Secondly, all indicators, metrics, and criteria should be gathered. For the next step, among gathered metrics, the ones that are more relevant are to be included. After that, an analysis would be required to acquire necessary data for the environmental, economic, and social metrics. Finally, an algorithm that allows decision-making on the alternatives would be applied.

On a different note, supplier selection can be categorized into two types of problems. The first type is called single sourcing in which one supplier satisfies all needs of the buyer. In the other type, namely multiple sourcing, satisfying a buyer would not be possible with just one supplier. Therefore, more than one supplier would be required to be involved in theprocess of supplier selection. Thereupon, allocating the optimal order quantities among the selected suppliers also requires to be considered within decision-making process of manufacturer(Azadnia et al., 2015a; Ghadimi et al., 2016b). There are different individual and integrated approaches for supplier selection. Many researchers solved the problem of supplier selection using various approaches including linear programming (LP) (Xu and Ding, 2011), Decision Making Trial and Evaluation Laboratory(DEMATEL) (Chang et al., 2011), Analytical Hierarchy Process (AHP) (Makui et al., 2016), Quality Function Deployment (QFD) (Wang, 2015), Neural Networks (NN) (Kuo et al., 2010), goal programming (Neumüller et al., 2016), Data Envelopment Analysis (DEA) (Shabanpour et al., 2017),Analytic Network Process (ANP) (Tavana et al., 2016; Ghadimi et al., 2016b), simulation-basedapproaches (Ghadimi and Heavey, 2014a;Byrne et al., 2013;Azadnia et al., 2015b), and Elimination and Choice Expressing

Reality (ELECTRE) (Azadnia et al., 2011) methods. A systematic literature review conducted by Chai et al. (2013) showed that AHP and LP are utilized in most frequent manner together with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).Zimmer et al. (2016) and Ghadimi et al. (2016a) also confirmed the popularity of AHP among industrial practitioners owing to its simplicity and flexibility.

Increasingly, green supplier selection issues have been addressed by academic researchers. Supplier selection problem is being considered from the TBL aspects described in Section 2.1 as well. Apart from these, the supplier selection problem is also being considered from the point of view of combining supplier selection with the order allocation problem in order to allocate optimal order quantities to selected suppliers using mathematical modelling. Based on the comprehensive literature review presented in Section 2.1, it can be perceived that the numbers of studies in which green supplier selection is focused on are abundant. However, a practical and comprehensive road map for procurement organizations in order to select the best suppliers and allocate optimal order quantities among them in a sustainable supply chainisof great importance and has been rarely addressed in the literature (Ghadimi et al., 2016a; Zimmer et al., 2016; Girubha et al., 2016). The contributions of this research study are as follows:

1) We address sustainable supplier selection and order allocation problem based on environmental, economic and social sustainability dimensions. We aim to bring this important problem under the attention of managers and CEOs of procurement organization in the field of sustainable supply chain and manufacturing.

2) We propose an integrated FAHP QFD-Fuzzy Assessment Method (FQFAM) to solve the sustainable supplier selection problem.

3) Using the scores obtained from the assessment method (FQFAM), a fuzzy multi-objective mix-integer non-linear programming model (MINLP) is developed to address the sourcing decisions of a typical manufacturing organization.

Furthermore, Section 2 presents the theoretical underpinning of this research activity. Section 3 introduces the FQFAM approach for sustainable supplier selection problem. Within the same section, a proposed model for order allocation problem is presented. In Section 4, a real-world application problem of a food and dairy productorganization is described. Section 5 reports the implementation of the FQFAM for the case study, and then reports the results. An illustration of the developed MINLP model is presented in Section 6. A sensitivity analysis of results is conducted, and results are described in Section 7. Within Section8, implications of the current research work for managers and industrial practitioners are fully discussed. Finally, Section 9 concludes the paper by a summary of the current research study and future studies.

2. Literature Review

The traditional supplier selection, where price, quality, and service are mostly considered as the evaluation criteria, was addressed in the literature. As the new era of sustainable procurement has come into existence, organizations made efforts to add environmental/ecological and social aspects to the traditional supplier selection criteria to establish a sustainable supply chain (Ghadimi et al., 2016a; Zimmer et al., 2016; Amindoust et al., 2013; Akman, 2014).Therefore, research articles were identified and utilized to conduct a comprehensive review of the literature in the domain of green/sustainable supplier selection. The results of the review are presented in Sections 2.1 and 2.2.

2.1. Green/sustainable supplier selection factors

Governmental legislations and the end-customers' sustainability awareness factors force manufacturing firms to consider the environmental issues in order to remain competitive (Azadnia et al., 2016; Ghadimi et al., 2016b; Ghadimi et al., 2017). Consequently, sustainability-incorporated suppliers are becoming more attractive for manufacturing companies. Hence, an appropriate supplier assessment that considers sustainability factors in the assessment procedureis needed. A literature review by Ho et al. (2010) confirmed thatquality, delivery, and price/cost are the commonly used factors in traditional supplier selection process where sustainability aspects have notbeen considered.

In order to meet the environmental regulations, many researchers and industrial practitioners have studied the factors of green supplier evaluation. Hsu et al. (2013) mentioned that air emissions, such as greenhouse effect and CO_2emission,areone of the most challenging issues in green supply chain management (GSCM). Therefore, they conducted a study explicitly for carbon management issues of supplier selection in GSCM problem. Genovese et al. (2013) stated that "in order to meet the increasing market pressures and demands from various stakeholder groups and to comply with more demanding environmental legislation, companies start to look at their supply chain to enhance their overall sustainability profile". Although environmental issues in the scope of supplier selection has been considered in a great extent by various researchers, the process of evaluation and selection needs to be done from the TBL perspective (Bai and Sarkis, 2010).

Kumar et al. (2014) mainly focused on supplier selection problem considering carbon foot printing issue. They considered emission factors to be used for footprint estimation in their assessment process together with traditional economic criteria, such as net price, distance, and shelf life or longevity of the product supplied. Büyüközkan and Çifçi (2012)tried to integrate their evaluation process into various environmental subcriteria falling into two main environmental criteria: green design and green competencies. Quality, cost, delivery, and flexibility are considered as economic evaluation criteria. Awasthi et al. (2010) evaluated suppliers based on various

environmental criteria, such as staff training regarding environmental targets, management commitment, and support, to improve environmental performance and green market share which deals with retention of customers with green purchasing habits.

Acombined consideration of economic, environmental, and social developmentisinterpreted as a sustainable development and sustainability, a TBL approach (Mehregan et al., 2014).A more practical attachment of environmental and social sustainability dimensions to traditional supplier selection problemis needed. Social subcriteria, e.g., child labour, human rights abuses, and irresponsible investment need to be incorporated into traditional/green supplier selection in order to have a TBL approach consideration of sustainability. Globally, social issues, such as workerhealth, humanrights, and safety, are being intensely recognised by manufacturing firms (Ghadimi and Heavey, 2014b; Bai and Sarkis,

2010;Zimmer et al., 2016; Ghadimi et al., 2016a; Azadnia, 2016; Ghadimi et al., 2017).

2.2.Integrated fuzzy approaches for green/sustainable supplier selection

Fuzzy set theory has been combined with many MCDM approaches to deal with the uncertain and imprecise data in real-life environments. In the green/sustainable supplier selection literature, many papers havebeen published utilizing fuzzy set theory as the basis/component of their supplier evaluation methodology. Table 1 lists these papers in order to highlight the applicability of fuzzy approach integrated with other approaches for sustainable/green supplier selection problem. It should be mentioned that the reviewed papers are journal papers, and all conference proceedings were excluded from the review process.

Table1

Journal articles in green/sustainable supplier selection.

Author(s)	Research objective	Proposed approach	Assessment criteria orientation
Chiouy et al. (2011)	Assign weights to various identified major selection with regard to CSR and sustainable	FAHP	Sustainable
Çifçi and Büyüközkan (2011)	Determine the appropriate criteria for evaluating	FAHP	Green
Parthiban et al. (2013)	Develop a strategic partnership policy using SWOT that enables the manufacturer to participate with top	Fuzzy SWOT and DEA	Green
Büyüközkan (2012)	Determine the criteria weights and fuzzy AD to rank	FAHP and Fuzzy AD	Green
Büyüközkan and Çifçi (2012)	Improve the green supply chain management initiatives.	Fuzzy-DEMATEL-	Green
Büyüközkan and Feyzioğlu (2008	Inclusion of fuzzy set theory with VIKOR methodology to deal with unquantifiable criteria to	Fuzzy-VIKOR	Green
Awasthi et al. (2010)	Assess the experts score and provide the final ranking for each suppli	Fuzzy-TOPSIS	Green
Shen et al. (2013)	Generate the overall performance score of each supplier.	Fuzzy-TOPSIS	Green
Govindan et al. (2012)	Evaluate suppliers based on TBL attributes.	Fuzzy-TOPSIS	Sustainable
Kannan, Jabbour et al. (2014)	Select green suppliers based on green supply chain	Fuzzy-TOPSIS	Green
Kannan et al. (2013)	Analyze the importance of multiple criteria by incorporating experts' opinion	Fuzzy-AHP-TOPSIS	Green
Buyukozkan and Cifci (2011)	Address sustainable supplier selection problem in a real-world case study in Turkish white goods	Fuzzy-ANP	Sustainable
Tuzkaya et al. (2009)	Find the interdependencies among criteria and rank	Fuzzy-PROMETHEE	Green
Bali et al. (2013)	Develop an approach to cope with situations with	Fuzzy-grey relational	Green

Apart from the threestudyreviews in Table 1 where TBL attributes were considered in the assessment, there are other studies that addressed the sustainable supplier selection problem. For example, Bai and Sarkis (2010) proposed a generic sustainable framework to assess suppliers. It was concluded that considering the attachment of the TBL approach in evaluating suppliers and sourcing activities may contribute significantly to firms' competitive advantages.Baskaran et al. (2012) deployed the grey system approach to facilitate the process of supplier selection for companies in Indian textile industry by enabling them to self-evaluate their own organizations.

2.3. Fuzzy AHP-QFD for sustainable supplier selection

The QFD model is known as a system for translating customer requirements into any measurement purposes (Cohen, 1995; Zhang et al., 2014). A four-phase QFD model was developed by Cohen (1995) for developing a new product. The application of QFD was initially introduced to the supplier selection problem by Ansari and Modarress (1994) where the roles of suppliers in the various phases of QFD were investigated. Many years later,Carnevalli and Miguel (2008) found some methodological difficulties of QFD, one of which was difficulty in interpreting the customers' voice. Accordingly, Dai and Blackhurst (2012) developed an

integrated AHP with QFD to enable the voice of company stakeholders in the process of supplier selection with respect to TBL attributes. They mentioned that extending the model to additional tiers of the supply chain would allow for the voice of the customer to translate through a larger part of the supply-chain network. It was also concluded that AHP-QFD is a promising method to deal with supplier selection problem (Dai and Blackhurst, 2012; Bhattacharya et al. 2010). In the current research work, the AHP-QFD developed in Dai and Blackhurst (2012) was extended to the FAHP-QFD in order to involve the manufacturing company's requirements into the process of determining sustainability sub criteria weights. The obtained weights were then utilized in an efficient Fuzzy Assessment Method (FAM) in order to rate suppliers. Uncertain and imprecise opinions in the process of weighting buyer's requirements were tackled by the inclusion of fuzzy set theory with the AHP. The main contribution of the proposed assessment method is including the decision makers' opinions inside the manufacturing company as sub criteria weights which are later utilized in the FAM (see Section 3.2.2 and Fig. 3). More details of the developed FAHP-QFD model are described in Section 3.2.1.

2.4. Green/sustainable order allocation

The problem of supplier selection has multiple conflicting objectives (Azadnia et al., 2015). Therefore, researchers tried to tackle this issue by addressing the sourcing decision issues in the supplier selection problem as well. There are a few research activities conducted with respect to integrating green/sustainable supplier selection problem with order allocation decision problem. Özgen et al. (2008) developed a multi-objective possibilistic linear programing order allocation model where AHP was

integrated with order allocation to address the problem of supplier selection and order allocation. Environmental criteria were considered in their assessment. Mafakheri et al. (2011) also applied AHP to rate the suppliers and fed

the results into a bi-objective function model where they maximized the utility function of suppliers and minimized the total supply chain costs.

Ghadimiet al. (2016) combined sustainable supplier selection with order allocation problem using fuzzy ANP-based audition check-list to evaluate suppliers, and then allocate orders to suppliers by means of a fuzzy bi-objective linear programming model. They managed to include two types of objective functions in their model. The first one deals with minimizing the total cost of purchasing which is consisted of product price, ordering, transportation, and holding costs. The second objective function takes into considerations the effects of sustainability issues to be maximized.

In this research activity, we tried to extend the literature of sustainable supplier selection and order allocation problem by developing a fuzzy MINLP. One of the main contributions of the proposed model is addressing the TBL attributes as the core constituents of the proposed model. In Section 3.3, a comprehensive definition of the proposed order allocation model is discussed and presented.

3.Research Methodology

The presented methodology has been developed to solve the purchasing issues in the case organization described in Section 4.As shown in Fig.1, the methodology consists of three main phases as follows:

1. Implementing FAHP-QFD for calculating theimportance weights of each sustainability subcriteria;

2. PerformingFAM for obtaining supplier's evaluation score for each sustainability dimenstion;

3. Constructing and solving the fuzzy multi-objective order allocation model in order to obtain the optimal order quantities for each supplier.

Each phase of the proposed method has been implemented step by step onthe real-world case study, presented in detail in Section 5.
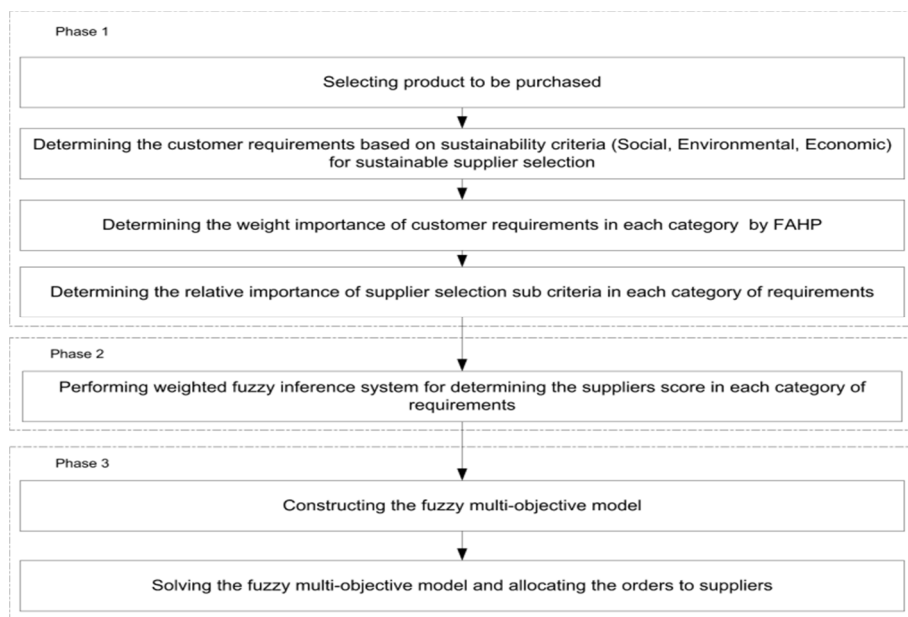

Fig. 1.The proposed methodology

3.2. FAHP QFD-Fuzzy Assessment Method (FQFAM)

3.2.1.Steps of FAHP-QFD (Phase 1)

Step 1.*Identifying buyer requirements and their relative importance weights.*

The process of building this matrix begins with the collection of the needs of buyer (WHATs) for the product or service based on the experienced experts' opinions inside the company. Then, FAHPis used to determine the weight of each requirement. For a description of implementing and use ofFAHP, see Chang (1996). A group of experts inside the companyneeds to be asked to make the pairwise comparison based on the fuzzy scale shown in Table2.

Table2
Fuzzy numbers and linguistic variables.

Fuzzy number	
(1,1,1	Just equal
(2/3,1,3/2	
(1,3/2,2	
(3/2,2,5/2	
(2,5/2,3	
(5/2,3,7/2	

In this paper, we focus on the customer requirement planning phase consisted of using a matrix called House of Quality (HOQ), which is used to develop procedures for identifying "WHAT" and "HOW". In the current research, HOQ uses matrices to investigate several relationships between buyer requirements regarding sustainability practises in the supplier in question ("WHAT") and three dimensions of sustainability sub criteria ("HOWs"). In other words, the buyer's requirements are transformed into TBL sustainability factors, which are then evaluated to establish an impact ranking (HOWs weights).

Two types of HOQ are utilized among academia and industry that are known as American and Japanese styles. A typical HOQ chart (American style) is shown in Fig. 2 and is created in six basic steps. Area E that is involved with correlating the HOWs is not used in the Japanese style. Since the Japanese style of HOQ is easy to use, it is employed in this paper.
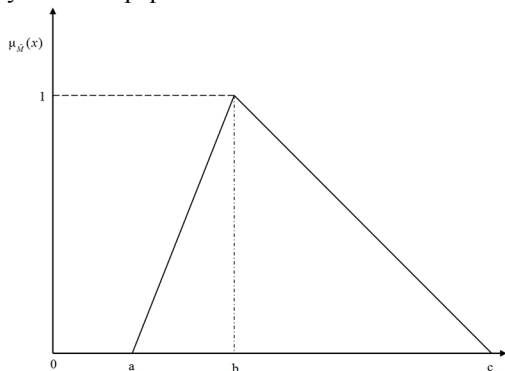

Fig. 2. House of quality (HOQ).

Step 2.*Identifying supplier evaluation subcriteria (HOWs).*

In this step, the supplier evaluation subcriteria and their related IFsto meeting the company's requirements are identified. As mentioned in Section 2.1,the selection criteria gathered by Ghadimi et al. (2016a) and Zimmer et al. (2016) can be utilized as these research studiespresent a well-defined categorization of the TBL attributes.Besides,decision-makers' (DMs) opinions inside the case company can add more evaluation subcriteria based on the company's needs.

Step 3. *Constructing relationship matrix of WHATs and HOWs.*

After identifying these subcriteria (HOWs), the relationship matrix of WHATs and HOWs, which shows the impact of each HOW on each WHAT, is constructed. In this research, as shown in Table3,five linguistic variables with their related triangular fuzzy numbers are used in order to express the DMs' opinions about the degree of relationship between company's requirements (WHATs) and supplier evaluation subcriteria (HOWs). These fuzzy numbers are presented by $A_i = (a_i, b_i, c_i)$ in which a_i and c_i are the lower and upper limits of the fuzzy number,respectively, while b_i is the element that denotes the closest fit. This phase in completed by calculating the importance weight of each supplier evaluation criterion using Eq. 2.

$$\tilde{R}_j^* = \sum_{i=1}^{m} W_i \otimes \tilde{R}'_{ij} \tag{1}$$

$$\tilde{R}'_{ij} = \frac{1}{N} \sum_{n=1}^{N} \tilde{R}_{ijn} \tag{2}$$

where:

$\tilde{R}_j^*$ = weight of jth supplier evaluation subcriterion

W_i = weight of ith buyer requirement

$\tilde{R}'_{ij}$ = average relationship score between i^{th} buyer requirement and j^{th} supplier evaluation subcriterion

$\tilde{R}_{ijn}$ = relationship score between i^{th} buyer requirement and j^{th} supplier evaluation subcriterion given by n^{th}DM

Table3
Linguistic scale for relative importance.

Triangular fuzzy number	
(1,1,2	Very weak (VW)
(1,2,3	Weak (W)
(2,3,4	Medium (M)
(3,4,5	Strong (S)
(4,5,5	

3.2.2. Fuzzy assessment method (FAM) (Phase 2)

In this phase, each supplier is evaluated according to the evaluation criteria and subcriteria using a FAM approach shown in Fig. 3.In the current research activity,the outputs of the HOQ matrix are applied as the weights to be multiplied by the sustainability subcriteria scores obtained by the FAM to acquire the final sustainability dimension scores. A brief explanation of the steps of thedeveloped FAM approach is given as follows:

For evaluating the supplier, some Ifsare to be defined for each supplier evaluation criterion. These used as the inputs variables for the FIS approach. Firstly, grades of membership are constructed using the crisp input and output variables for linguistic terms of fuzzy sets.Then,fuzzificated variables are utilizedto storeexperts' knowledge translated into fuzzy rules that are stored in a fuzzy rule base. Based on the consultant with DMs,the crisp input and output variables'membership grades are defined. For input variables, low, medium, and high membership grades were assigned; low, low to medium, medium, medium to high, and high were defined as membership grades foroutput variable. The fuzzy evaluation was implemented using MATLAB fuzzy logic toolbox. Finally, Eqs.3-5. are used tocalculateeachsustainabilityelementscore of each supplier.

It is worth emphasizing that the results obtained from FAHP-QFD phase (sub criterion weight) of the methodology are multiplied to the defuzzification results in order to obtain the weighted score of each sub criterion.
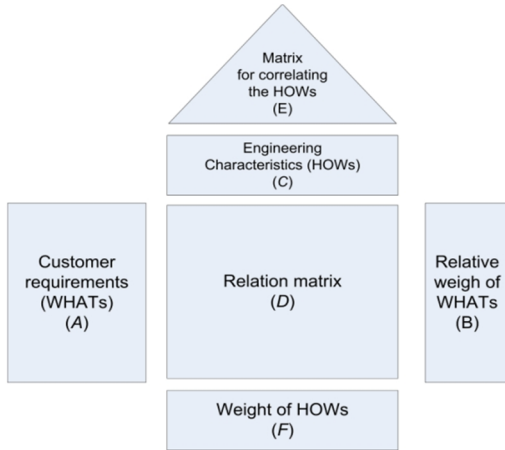

Fig. 3. The fuzzy assessment model.

$$\psi_i = \sum_i \tilde{R}_j^* \psi_{ij} \qquad (3)$$

$$q_i = \sum_i \tilde{R}_j^* q_{ij} \qquad (4)$$

$$E_i = \sum_i \tilde{R}_j^* E_{ij} \qquad (5)$$

where

ψ_{ij} Score of supplier i in j^{th}subcriterion of social element

q_{ij} Score of supplier i in j^{th}sub criterionof economic qualitative element

E_{ij} Score of supplier i in j^{th}sub criterionof environmental element

q_i Score of supplier i in economic qualitative sustainability

E_i Score of supplier i in environmental sustainability

ψ_i Score of supplier i in social sustainability

3.3.Fuzzymulti-objectiveMINLP model for sustainable order allocation (Phase 3)

In this section, the multi-objective nonlinear model is presented. The model aims at allocating the optimum order quantities of a product to n supplier considering all three aspects of sustainability. The beginning and end of the horizon inventory level are assumed to be zero. Also, there is no quantity discount, and one product is to be purchased from suppliers. Besides, no demand variability is taken into account in problem formulation. This current research paper proposes a fuzzy multi-objective MINLP model for the sustainable supplier selection and order allocation problem with multiple sourcing consisted of four objectives: minimizing the total cost of annual purchasing, maximizing economic sustainability, maximizing environmental sustainability, and maximizing social sustainability. A set of constraintsisalso associated withthis model such as buyer company's demand, supplier'sdelivery, suppliers' capacity, and perfect rate of product to be delivered. A detailed explanation of the proposed model is described as follows:

Notations

I Number of suppliers

Q Total order quantity to all suppliers in each period

Q_i Order quantity to supplier$i$ in each period

N Number of periods

n Number of suppliers

P_i Product price of supplier i

r Holding cost ratio

D Demand of product

T Length of each period

T_i Time period in which the purchased order quantity from supplier$i$ is used

A_i Ordering cost of supplier i

ϕ_i Transportation cost of supplier i for each kg of product

6

q_i Score of supplier i in economic qualitative sustainability obtained by fuzzy QFAM

E_i Score of supplier i in environmental sustainability obtained byfuzzyQFAM

ψ_i Score of supplier i in social sustainability obtained byfuzzyQFAM

C_i Capacity of supplier i

L_i Late delivery rate of supplier i

L Acceptance level of delay rate

η_i Perfect rate of supplier i

η Minimum acceptance rate of perfect

x = product i
       percentage of Q allocation to supplier i

$Y_i \begin{cases} 1 & \text{if an order allocated to supplier } i \\ 0 & \text{otherwise} \end{cases}$

- **Objective functions**

Cost objective function: The Total cost of Annual Purchasing (TAP) includes annual purchasing cost, annual transportation cost, annual ordering cost, and annual

holding cost. In this research, the cost objective function is developed by incorporating the transportation cost into a nonlinear model developed by Ghodsypour and O'Brien (2001). This objective function is aimed at minimizing the total cost of annual purchasing which can be stated as follows:

TAP= annual purchasing cost+ annual ordering cost + annual holding cost+ annual transportation cost

Considering the economic order quantity model, the economic order quantity is presented in Eq.6. We consider the situation in which there are *n* suppliers to purchase from them. Therefore, Q might be divided between suppliers in order to reduce the total costs of the system, as shown in Fig. 4.

$$Q = \sqrt{\frac{2DA}{rp}} \tag{6}$$

$$Q = \sum_{i=1}^{n} Q_i \tag{7}$$

$$Q_i = x_i Q \tag{8}$$

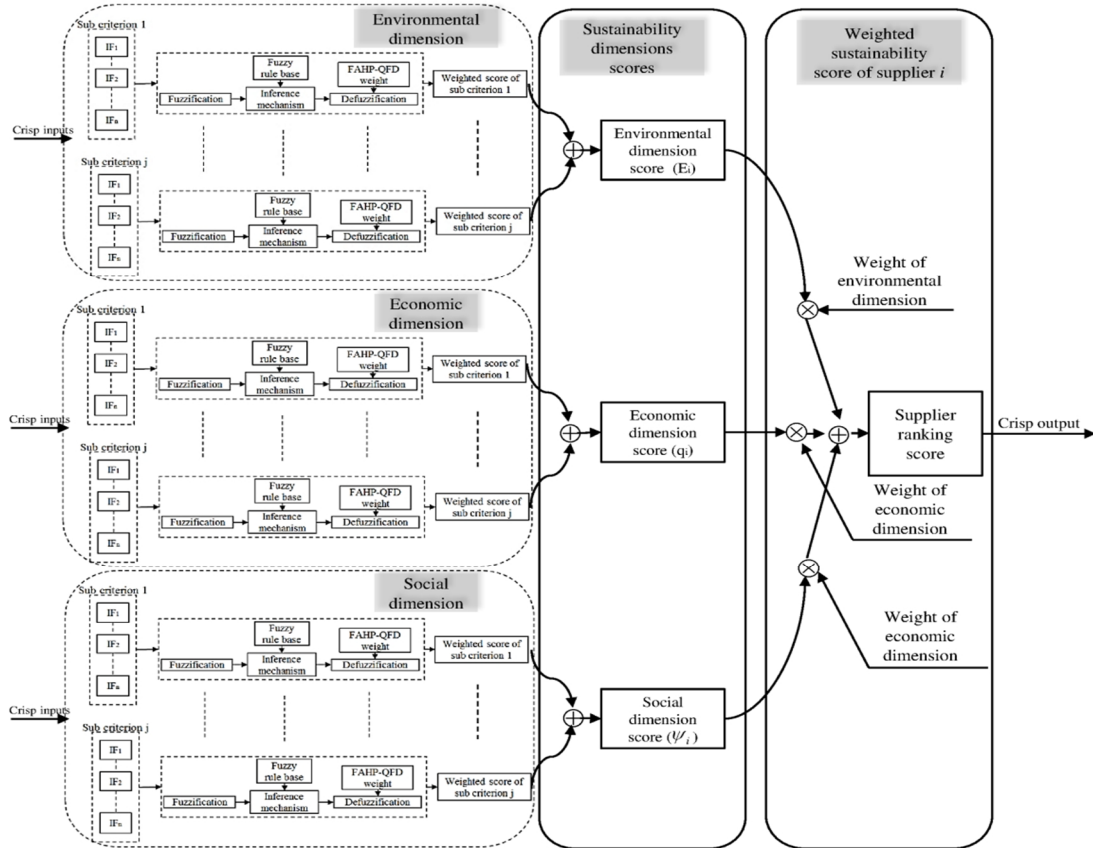$$T_i = x_i T \tag{9}$$

$$\sum_{i=1}^{n} x_i = 1 \tag{10}$$

Fig. 4. The supplier inventory graph.

Annual transportation cost (ATC): considering that the annual order quantity purchased from the ith supplier is $x_i D$ and the transportation cost of ith supplier is ϕ_i,

Annual purchasing cost (APC): as the annual order Quantity purchased from i^{th} supplier is $x_i D$, *APC* can be formulated as follows:

$$ATC = \sum_{i=1}^{n} x_i . D . \phi_i \qquad (11)$$

$$APC = \sum_{i=1}^{n} x_i D P_i \qquad (12)$$

Annual ordering cost (AOC): the annual ordering cost is achieved by multiplying ordering cost of each period to number of periods in a year. Therefore:

$$AOC = (\sum_{i=1}^{n} A_i Y_i).N = (\sum_{i=1}^{n} A_i Y_i) \frac{D}{Q}) \qquad (13)$$

Hence, holding cost in each period can be calculated using Eq. 3.16:

Annual holding cost (AHC): According to Fig. 3, the average inventory level of ith supplier (AI$_i$) and average holding cost in T_i (AHCT_i) are calculated using Eqs. 3.14 and 3.15, respectively.

$$AI_i = \frac{x_i Q}{2} \qquad (14)$$

$$AHCT_i = (\frac{x_i Q}{2} , r P_i \qquad (15)$$

$$HPC = \sum_{i=1}^{n} \frac{x_i Q}{2} r P_i T_i \qquad (16)$$

Besides,

$$T_i = \frac{x_i Q}{D} \qquad (17)$$

Therefore, HPC can be written as follows:

$$HPC = \frac{rQ^2}{2D} (\sum_{i=1}^{n} x_i^2 P_i) \qquad (18)$$

Moreover, annual holding cost is calculated by multiplying *HPC* to *N,* so:

$$AHC = \frac{rQ^2}{2D} (\sum_{i=1}^{n} x_i^2 P_i) N = \frac{rQ^2}{2D} (\sum_{i=1}^{n} x_i^2 P_i) \frac{D}{Q} = \frac{rQ}{2} (\sum_{i=1}^{n} x_i^2 P_i) \qquad (19)$$

By summing up AHC, ATC, AOC, and APC, TAP is calculated as follows:

$$TAP = \sum_{i=1}^{n} x_i . D . \phi_i + (\sum_{i=1}^{n} A_i Y_i) \frac{D}{Q} + \frac{rQ}{2} (\sum_{i=1}^{n} x_i^2 P_i) + \sum_{i=1}^{n} x_i D P_i \qquad (20)$$

The optimum order quantity (Q) can be calculated by setting the derivative of *TAP* equal to zero.

$$\frac{\partial (TAP)}{\partial Q} = 0 \Rightarrow Q = \sqrt{\frac{2D \sum_{i=1}^{n} (A_i Y_i)}{r (\sum_{i=1}^{n} x_i^2 P_i)}} \qquad (21)$$

By replacing Q in Eq. 19, the finalized cost objective function appears as follows:

$$Min\ Z_1 = \sqrt{2Dh(\sum_{i=1}^{n} A_i Y_i)(\sum_{i=1}^{n} x_i^2 P_i)} + \sum_{i=1}^{n} x_i P_i D + \sum_{i=1}^{n} x_i \phi_i D \qquad (22)$$

Environmental objective function: each supplier's final environmental sustainability score can be maximized by the objective function presented in Eq.23. Suppliers'

scores in environmental sustainability dimension are symbolized as E_i:

$$Max\ z_2 = \sum_i x_i E_i D \tag{23}$$

Social objective function: each supplier's final social sustainability score can be maximized by the objective function presented in Eq. 24. Suppliers' scores in social sustainability dimension are denoted as ψ_i:

$$Max\ z_3 = \sum_i x_i \psi_i D \tag{24}$$

Economic sustainability objective function: each supplier's score(q_i)in economic sustainability dimension, which is calculated by FQFAM in Section 3.2,isused as a coefficient for x_i which denotes the percentage of product to be allocated to supplier i:

$$Max\ z_4 = \sum_i x_i q_i D \tag{25}$$

Constraints

Demand constraint:this constraint stipulates that all of the buyer demands should be met:

$$\sum_i x_i D = D \tag{26}$$

$$\sum_i x_i = 1 \tag{27}$$

Capacity constraint: considering that this constraint makes sure that the number of ordered products

fromsupplier *I*will be within the supplier's production capacity:

$$x_i D \le C_i \tag{28}$$

Delivery constraint: this constraint demands that the total late delivery of the product ordered from suppliers has tobe equal to or less than the company requirement (acceptance delay rate).

$$\sum_i x_i L_i D \le L \tag{29}$$

Perfect rate constraint: this constraint stipulates that the total perfect rate of product purchased from all suppliers must be equal to or greater than the acceptance rate.

$$\sum_i x_i \eta_i D \ge \eta \tag{30}$$

The integer variables conditions need to be ensured after all constraints are constructed. These variables are: ifY_i is zero, x_i is also zero, and if Y_i is 1, $x_i$must be greater than zero. The constraints presented in Eqs.31 and 3.39 can satisfy these conditions by considering that x_i is less than one:

$$x^i \le Y_i \tag{31}$$

$$x_i \ge \varepsilon Y_i \tag{32}$$

The resulting multi-objective MINLP model appears as follows:

$$Min\ Z_1 = \sqrt{2Dh(\sum_{i=1}^n O_i Y_i)(\sum_{i=1}^n x_i^2 P_i)} + \sum_{i=1}^n x_i P_i D + \sum_{i=1}^n x_i \phi_i D \tag{33}$$

$$Max\ Z_2 = \sum_i x_i E_i D \tag{34}$$

$$Max\ Z_3 = \sum_i x_i \psi_i D \tag{35}$$

$$Max\ Z_4 = \sum_i x_i q_i D \tag{36}$$

Subject to:

$$\sum_i x_i D = D \tag{37}$$

$$\sum_i x_i = 1 \tag{38}$$

$$x_i D \le C_i \tag{39}$$

$$\sum_i x_i L_i D \le L \tag{40}$$

$$\sum_i x_i \eta_i D \ge \eta \tag{41}$$

$$x_i \le Y_i \tag{42}$$

$$x_i \ge \varepsilon Y_i \tag{43}$$

3.3.1. Weighted max-min solution approach

Weber and Current (1993) proposed a general multi-objective model for the supplier selection as follows:

$$Min \ Z_1, \ Z_2,...,Z_k \tag{44}$$

$$Max \ Z_{k+1}, \ Z_{k+2},...,Z_p \tag{45}$$

Subject to:

$$x \in X_d \tag{46}$$

$$X_d = \{x \ / \ g_s(x) \le b_s, s = 1, 2,..., m\}$$

$Z_1, \ Z_2,...,Z_k$ are utilized when the negative objective functions for minimization, such as cost, late delivery, etc., are involved. Contrarily, $Z_{k+1}, \ Z_{k+2},...,Z_p$ are applied when dealing with maximization objective functions such as quality, social, environmental criteria, and so on. The set of feasible solutions is denoted as X_d utilized to satisfy the set of system and policy constraints. A tolerance limit and membership function $\mu(Z_j(x))$ for j^{th} fuzzy goals might be defined by DM in order to deal with some sort of situations where it is nearly impossible to achieve an optimal solution simultaneously for all objective functions. According to Zimmerman (1978), a fuzzy multi-objective model can be formulated as follows:

Find a vector $x^T = [x_1, x_2..., x_n]$ to satisfy

$$\tilde{Z}_k = \sum_{i=1}^{n} c_{ik} x_i \le \sim Z_k^0 \ \ k = 1, 2,..., p \tag{47}$$

$$\tilde{Z}_l = \sum_{i=1}^{n} c_{il} x_i \ge \sim Z_l^0 \tag{48}$$

$$l = p+1, p+2,..., q$$

Subject to

$$g_s(x) = \sum_{i=1}^{n} a_{si} x_i \le b_s, \ s = 1,..., \tag{49}$$

$$x_i \ge 0, \ i = 1, 2,..., n \tag{50}$$

where c_{ik}, c_{il}, a_{si}, and b_s are crisp values. The fuzzy environment is noted by "~". In the constraints set, symbol "$\le\sim$" denotes the fuzzified version of "$\le$" and is linguistically interpreted as "essentially smaller than or equal to". Likewise, symbol "$\ge\sim$" means "essentially greater than or equal to". Z_l and Z_k are expressed as the aspiration levels that the DM intends to achieve. In 1978, Zimmermann extended his own fuzzy linear programming approach to the fuzzy multi-objective LP problems. Objective functions Z_j with $j=1,...,q$ were expressed by fuzzy sets with linearly increasing membership functions from 0 to 1. Using the membership function of objectives, each objective function is divided into its minimum and maximum values. Z_k and Z_l denote the linear membership functions for minimization and maximization goals presented in Eqs. 3.51 and 3.52 as follows:

$$\mu_{zk}(x) = \begin{cases} 1 & \text{for } Z_k \le Z_k^- \\ f_{\mu z_k} = (Z_k^+ - Z_k(x))/(Z_k^+ - Z_k^-) & \text{for } Z_k^- \le Z_k(x) \le Z_k^+ \quad (k = 1, 2,..., p) \\ 0 & \text{for } Z_k \ge Z_k^+ \end{cases} \tag{51}$$

$$\mu_{zl}(x) = \begin{cases} 1 & \text{for } Z_l \ge Z_l^+ \\ f_{\mu zl} = (Z_l(x) - Z_l^-)/(Z_l^+ - Z_l^-) & \text{for } Z_l^- \le Z_l(x) \le Z_l^+ \quad (l = p+1, p+2,..., q) \\ 0 & \text{for } Z_l \le Z_l^- \end{cases} \tag{52}$$

where Z_k^- and Z_l^+ are the best solutions of the model which are obtained through solving each objective function separately. Moreover, Z_k^+ and Z_l^- are the worst values of each objective function. Considering the weight of each objective function, Lin (2004) proposed a weighted max–min model for multi-objective fuzzy programming as follows:

$$Max \ \lambda \tag{53}$$

Subject to:

$$w_j \lambda \le f_{\mu z_j}, \quad J = 1,...,q \tag{54}$$

(for all objective functions)

$$g_r(x) \le b_r \text{ (for all constraints)} \tag{55}$$

$$\lambda \in [0,1] \tag{56}$$

$$\sum_{j=1}^{q} w_j = 1, \ w_j \ge 0 \tag{57}$$

$$x_i \ge 0, \ i = 1,...,n \tag{58}$$

Each objective function weight is determined based on the DMs' expert ideas inside the company using FAHP. Our proposed MINLP model is structured and solved based on Eqs. 3.59 - 3.70.Therefore, the final model can be formulated as follows:

$$\text{Max } \lambda \quad \text{Subject to:} \tag{59}$$

$$w_j \lambda \leq f_{\mu z_j}, \quad J = 1,...,q \tag{60}$$

(for all objective functions)

$$\sum_i x_i D = D \tag{61}$$

$$\sum_i x_i = 1 \tag{62}$$

$$x_i D \leq C_i \tag{63}$$

$$\sum_i x_i L_i D \leq L \tag{64}$$

$$\sum_i x_i \eta_i D \geq \eta \tag{65}$$

$$x_i \leq Y_i \tag{66}$$

$$x_i \geq \varepsilon Y_i \tag{67}$$

$$\lambda \in [0,1] \tag{68}$$

$$\sum_{j=1}^{q} w_j = 1, \ w_j \geq 0 \tag{69}$$

$$x_i \geq 0, \ i = 1,...,n \tag{70}$$

It is worth mentioning that all of the objective functions are convex. The convexity of the first objective function wasshownby Ghodsypour and O'Brien (2001). Likewise, Z_2, Z_3, and $Z_4$are convex due to their linear nature. Therefore, it can be perceived that feasible region of the problem is convex. Moreover, the objective function of the above-mentioned problem is linear and convex. Consequently, due to convexity nature of the problem, each local optimal solution is the global optimal solution to the problem.

4. Real-world ApplicationProblem

The present quality of life is closely associated withthe global chemical industry. However, the current working practices are under increasing pressure to be aligned with sustainable initiatives (Veleva et al., 2003). Packaging films manufacturers that constitute a small part of chemical industry are massively involved infood and pharmaceutical industries that are striving to maintain their competitive edge regarding incorporating sustainability practises into their supply chain operations. Manufacturing organizations in this specific type of industry want to improve their sustainability practises not only internally, but also externally asthey are concerned

about the sustainability level of the suppliers that are providing these packaging films for them. Sustainable performance needs to be addressed all over the supply chain that can be achieved by establishing strategic partnerships with environmentally, economically, and socially dominant suppliers.

Aleading food and pharmaceutical products organization located in Iran, namely Kaleh, faces purchasing decisions where they are obligated by their stakeholders to consider sustainability guidelines in their procurement operations. Currently, the supplier selection and order allocation decisions are made by the planning department where they consider traditional supplier selection attributes in their decisions. The organization is striving to adapt itself tothe global sustainability directives in order to export its finished products all over the globe with the maximum sustainability standards. Consequently, the managers of the company were and still are interested in integrating environmental and more broadly sustainable practises into their supply chain activities. It is worth mentioning that there are many other research activities being conducted in the company covering all the possible aspects of sustainable supply chain management. Hence, based on the discussions with top managers of the organization, it was initially agreed to consider one special type of packaging film that is highly used in packaging various types of products in the company. The core materials used for the production of this type of film are Polyamide 6 (PA 6), Polyvinyl chloride (PVC), and Low-Density Polyethylene (LDPE). The cumulative thickness of this type of film has to be 160 micrometres. The thickness of each type of material used in this packaging film is tabulated in Table 4 in micrometre. These products are being procured by three suppliers, named as S1, S2, and S3.

Table 4
Thickness of each type of material.

Material Type	Required acceptable thickness range
PA 6	50-58
PVC	84-96
LDPE	14-20

5. Using FQFAM for Identifying the Suppliers' Sustainability Scores (Phases 1 and 2)

5.1. Identifying buyer requirements and their relative importance weight (Phase 1 - Step 1)

In this section of the methodology, FAHP-QFD approach was implemented individually for each sustainability dimension. For each of sustainability dimensions, there are some essential properties of products (varying case by case) required by themanufacturingorganizationthat are considered in this study. Although these requirements vary case by case, but the list of "WHATs" tabulated in Table 5contains the relevant attributes required in most of the purchases.
The manufacturer organizations' DMs have indicatedthat on-time delivery, environmental competencies, and

technological capability are to be the priority issues. Besides, the increasing tendency of stakeholders to health and safety practices in the suppliers' company is also

another critical factor in ensuring long-term business relations with the supplier.

Table 5
Manufacturer's requirements.

Sustainability dimension	WHATs	Importance weight
Environmental Sustainability (R₁)	(C_1) Product compliance with environmental directives.	0.500
	(C_2) Preserving company's competitive edge regarding environmental durability of manufactured product in designated stores.	0.500
Economic Sustainability (R₂)	(C_3) Product compliance with design and manufacture procedures.	0.448
	(C_4) Punctuality of deliveries regarding the specified delivery date.	
	(C_5) Expanding product/service performance to preserve company competitive edge.	0.276
		0.276
Social Sustainability (R₃)	(C_6) Punctuality of employees regarding social sustainability duties.	0.202
	(C_7) Securing employees health and their work place.	
	(C_8) Commitment of CEOs to consider voice of stakeholder's for social responsiveness.	

The importance weight of each "WHAT" is calculated by means of the FAHP methodology shown in Table 5. The DMs as one group of experts were asked to use the linguistic weighting variables to assess these weights. Owing to limitation of space, the tables and calculations related to the FAHP approach are not presented in this paper. The final FAHP importance "WHATs" weights for each sustainability dimension are calculated using Microsoft Excel.

5.2. Identifying the sustainability sub criteria and IFs (Phase 1 – Step 2)

As discussed in Section 2.1, the categorization detailed in Ghadimi et al. (2016a) has been adopted for this study. These sub criteria were validated by discussions held with a team of experts consisting of five individuals (sales manager, general manager, inventory manager, design department representative, and material purchasing represantative). Finally, environmental, economic, and

social sustainability sub criteriawere defined, and three possible suppliers (S1, S2, S3) were evaluatedfor sustainable supplier selection and order allocation problem decision-making. Figs. 5-7 show the selected criteria considered in this study.
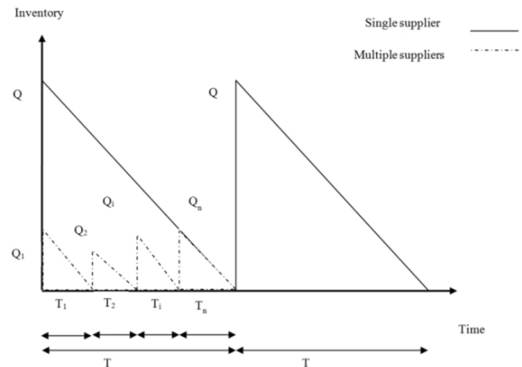

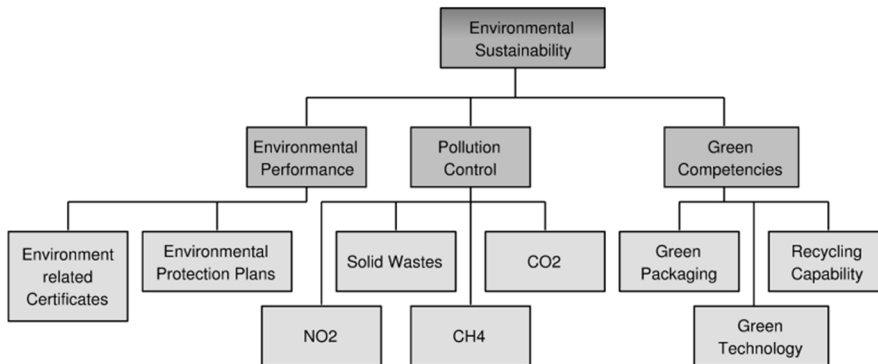Fig. 5. Environmental sustainability subcriteria and IFs.

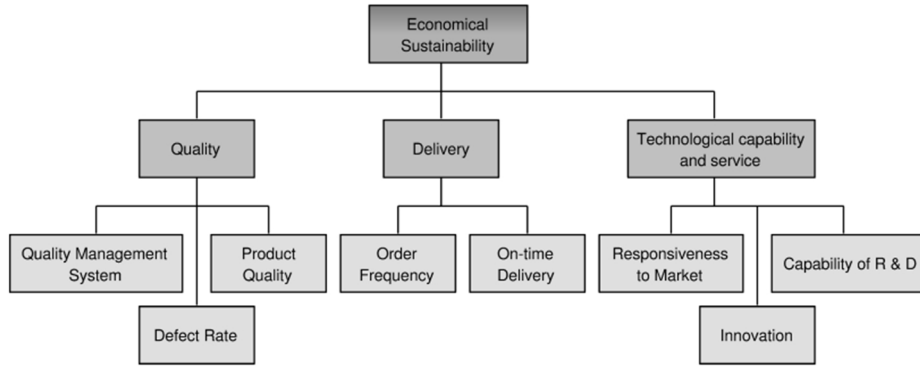Fig. 6. Economic sustainability sub criteria and IFs.

12

Fig. 7.Social sustainability sub criteria and IFs.

5.3. Obtaining the weights of the sustainability sub criteria (Phase 1 – Step 3)

The next step of the methodology deals with defining the "HOW"-"WHAT" co-relation scores and weighting the "HOWs". On the impact of each "HOW" on each "WHAT", each DM was asked to express an opinion, using one of the five linguistic variables presented in Table 3. The expressed opinions by the five DMs together with the final weights of HOWs obtained from the calculations using Eqs. 3.1 and 3.2are shown in Table 6. These final weights of HOWs, consisted of each sustainability dimension sub criterion, are utilized to derive the final score of each supplier in the next section.

Table 6
Final weights of HOWs.

R1

WHATs	HOWs														
	Environmental performance					Green competencies					Pollution control				
	DM1	DM2	DM3	DM4	DM5	DM1	DM2	DM3	DM4	DM5	DM1	DM2	DM3	DM4	DM5
C1	VS	VS	VS	VS	VS	S	S	M	S	S	M	S	M	S	S
C2	M	W	M	M	M	VS	VS	VS	VS	VS	M	M	S	M	W
Weight of	0.329					0.380					0.291				

R2

	Quality					Delivery					Technical capability				
	DM1	DM2	DM3	DM4	DM5	DM1	DM2	DM3	DM4	DM5	DM1	DM2	DM3	DM4	DM5
C3	VS	VS	VS	VS	VS	VW	VW	VW	VW	VW	M	W	M	W	W
C4	W	M	M	M	M	VS	VS	VS	VS	VS	M	M	S	S	M
C5	VW	VW	VW	VW	VW	M	M	M	S	M	VS	VS	VS	VS	VS
Weight of	0.318					0.359					0.323				

R3

	Health and safety					Employee practice					Local community influence				
	DM1	DM2	DM3	DM4	DM5	DM1	DM2	DM3	DM4	DM5	DM1	DM2	DM3	DM4	DM5
C6	S	M	S	VS	S	VS	VS	VS	VS	VS	VW	VW	VW	VW	VW
C7	VS	VS	VS	VS	VS	S	S	S	VS	S	W	W	VW	VW	W
C8	M	M	M	M	M	M	M	S	S	S	S	S	S	S	S
Weight of	0.395					0.386					0.219				

5.4. Fuzzy assessment method (FAM) (Phase 2)

Data related to each sustainability dimension, its corresponding subcriteria, and presented in this section utilized in obtaining each supplier's sustainability score (Table 7). These data were gathered through a comprehensive 6 month data gathering phase in order to come up with reliable and practical information which can help to derive percise results. Quantitative and quantitative data aregathered using the companies historical records, ISO documentations and discussion with five DMs inside each supplier's company. Data related to CO_2, NO_2, and CH_4 emissions to air where collected from Plastic Europe database version 3.0 (Plastics Europe, 1996; Plastics Europe,1998; Plastics Europe, 1999). The amount of emissions during manufacturing 100gr of the specific type of packaging film considered in this study, consisting of PVC, PA 6, and LDPE,iscalculated and utilized as input data tabulated in Table 7.Definitions of the rest ofIFs considered in this study are explained as follows:

Environmental related certificates (EC): Passing Environmental Certificate verification of supplier i

$$\begin{cases} 1 : \text{Do nothave} \\ 2 : \text{Have but not being implemented completely} \\ 3 : \text{Have and being implemented well} \end{cases}$$

Environmental protection plans (EPP): Having environmental protection plans of supplier i

$$\begin{cases} 1 : 0 \text{ to } 50\% \text{ done} \\ 2 : \text{more than } 50\% \text{ done} \\ 3 : \text{Have done completely} \end{cases}$$

Solid waste (SW): The percentage of solid waste that is produced during manufacturing 1 kg of the product being assessed.

Green packaging (GP): The level of environmetally friendly materials used in packaging

$$\begin{cases} 1 : \text{not at all} \\ 2 : \text{less than } 50\% \text{ used} \\ 3 : \text{more than } 50\% \text{ used} \end{cases}$$

Recycling capability (RC): The level of recycling capability of supplier i

$$\begin{cases} 1 : \text{not at all} \\ 2 : \text{less than } 50\% \\ 3 : \text{more than } 50\% \end{cases}$$

Green technology (GT): The level of technology being utilized in supplier I, such as machineries, complies with green issues.

$$\begin{cases} 1 : \text{not at all} \\ 2 : \text{less than } 50\% \\ 3 : \text{more than } 50\% \end{cases}$$

Quality management system (QMS): The level of implementing QMS in supplier i

$$\begin{cases} 1 : \text{do nothave} \\ 2 : \text{has but not being implemented completely} \\ 3 : \text{has and being implemented well} \end{cases}$$

Product quality (PQ): The quality level of finished product audited by supplier i

$$\begin{cases} 1 : \text{low} \\ 2 : \text{medium} \\ 3 : \text{high} \end{cases}$$

Defect rate (DR): Number of defected finished goods detected by manufacturer quality control team supplied from supplier i.

On-time delivery (OTD): Average number of delays in days occurring with supplier i for delivering finished products.

Quality of transportaion and delivery (QTD): Level of quality of transportation and delivery of finished goods provided by supplier i to buyer

$$\begin{cases} 1 : \text{low} \\ 2 : \text{medium} \\ 3 : \text{high} \end{cases}$$

Technology level (TL): Type of technology that is being used by supplier i to manufacture product being assessed

$$\begin{cases} 1 : \text{old} \\ 2 : \text{fairly new} \\ 3 : \text{new} \end{cases}$$

Capability of R&D (CRD): Total Number of R&D projects that would be conducted during 1 year by supplier i to meet the current and future demands of the firm.

Health and safety incident (HSI): Percentages of critical incidents (Hospitalized/Fatalities) that would happen for the workers during manufacturing in1 year in supplier i facility.

OHSAS 18001 (OH): The level of OHSAS 18001 certificate implementation

$$\begin{cases} 1 : \text{do nothave} \\ 2 : \text{has but not being implemented completely} \\ 3 : \text{has and being implemented well} \end{cases}$$

Health and safety practice (HSP): Average number hours being spent to educate workers about how to establish and practice Healthy and safe works during one year in supplier i.

Disciplinary and security practices (DSP): trained security personnel percentage concerning aspects of human rights that are relevant to the organizations's operations.

Employee training (ET): Average number of hours that would be spent by employer to train each employee regarding their awareness of social and cultural sustainability practices.

Job opportunity (JO): Total number of opportunities of employment contributed by supplier i during one year.

Supporting educational institution (SEI): Total number of academic projects that supplier i would be involved with universities and educational institutions during one year.

Grant and donation (GD): The percentage of total profit gained during 1 year by supplier i donated to make and support strategic social investments that have a lasting benefit on society.

Table 7
Input data.

Sustainability dimension	IF	Unit	Input (S_1, S_2, S_3)	Sustainability dimension	IF	Unit	Input (S_1, S_2, S_3)
Environmental Sustainability	*input data for environmental performance*			Social Sustainability	*input data for health and safety*		
	EC	dimensionless	(2, 3, 3)		HSI	%	(6, 7.7, 5)
	EPP	dimensionless	(2, 3, 3)		OH	dimensionless	(2, 2, 3)
	input data for pollution control				HSP	hours/year	(25, 25, 30)
	SW	%	(5, 4 , 5)		*input data for employment practices*		
	CO_2	gr/100 gr of product	(0.322408, 0.318275, 0.307964)		DSP	%	(4, 6.15, 6)
	NO_2	gr/100 gr of product	(0.000939, 0.000921, 0.00088)		ET	hours/year	(20, 30, 40)
	CH_4	gr/100 gr of product	(0.00307, 0.003045, 0.002966)		JO	numbers/year	(33, 46, 79)
	input data for green competencies				*input data for local community influence*		
	GP	dimensionless	(1, 3, 2)		SEI	number/years	(6, 8, 12)
	RC	dimensionless	(2, 2, 3)		GD	%	(1, 2, 2)
	GT	dimensionless	(3, 2, 2)				
Economic sustainability	*input data for quality*			Economic sustainability	*input data for delivery*		
	QMS	dimensionless	(2, 3, 3)		OTD	average number/year	(2, 4, 4)
	PQ	dimensionless	(3, 3, 3)		QTD	dimensionless	(3, 3, 2)
	DR	average number/year	(4, 5, 3)		*input data for technological capability*		
					TL	dimensionless	(2, 2, 2)
					CRD	number/year	(6, 7, 10)

In the next step, the membership functions parameters were calculated and fuzzy rules were generated using MATLAB fuzzy logic package. In order to have definite evaluation, the entire knowledge was transformed into the if-then rules. Fig.8 shows that the rules from the rule base for local community influence subcriteria for illustration purposes. Finally, overall score for each subcriterion of environmental, economic, and social sustainability was calculated, and then the environmental, economic, and social sustainability dimensions scores were obtained using Eqs. 3.3-3.5. Table 8shows the calculated scores for the selected subcriteriarelated to each sustainability dimension.
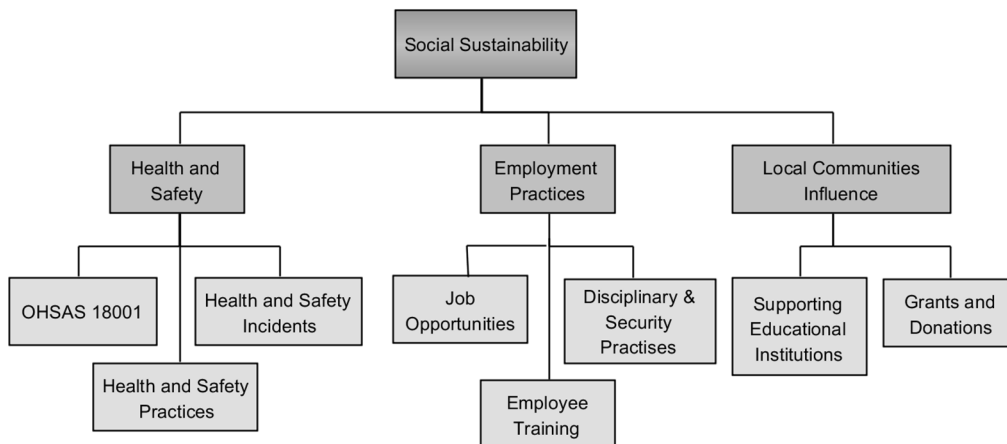

Fig. 8. Rule base for local community influences.

Table 8
Obtained scores.

IF	Subcriteria	Weighted subcriteria score (S_1)	Weighted subcriteria score (S_2)	Weighted subcriteria score (S_3)
Overall score for environmental sustainability element				
EC EPP	*environmental performance*	0.165	0.303	0.303
SW CO$_2$ NO$_2$ CH$_4$	*pollution control*	0.178	0.216	0.235
GP RC GT	*green design*	0.145	0.218	0.218
Environmental sustainability score		0.488	0.737	0.756
Overall score for economic sustainability element				
QMS PQ DR	*quality*	0.269	0.269	0.272
OTD QTD	*delivery*	0.243	0.209	0.130
TL CRD	*technological capability*	0.138	0.149	0.185
Economic sustainability score		0.651	0.627	0.587
Overall score for social sustainability element				
In OH HSP	*health and safety*	0.202	0.176	0.296
DSP ET JO	*employment practices*	0.188	0.223	0.249
SEI GDS	*local community influence*	0.073	0.094	0.109
Social sustainability score		0.463	0.494	0.655

As it can be percieved from Fig. 9, supplier S3 is ahead of S1 and S2 in considering environmental and social sustainability issues in its manufacturing operations. However, supplier S3 with overall score of 0.587 is ranked as the third supplier in economic sustainability consideration, which is justifiable as they are obviously spending more budget on improving envionmental and social aspects of their production activities. Supplier S1 is the weakest when it comes to incorporating social and environmental sustainability in its manufacturing activities. Although supplier S1 is doing a great job in keeping their economic sustainability score at a high level, taking into account the other two dimensions of sustainability is vital as they claim that they want to improve their competitive edge in the market.
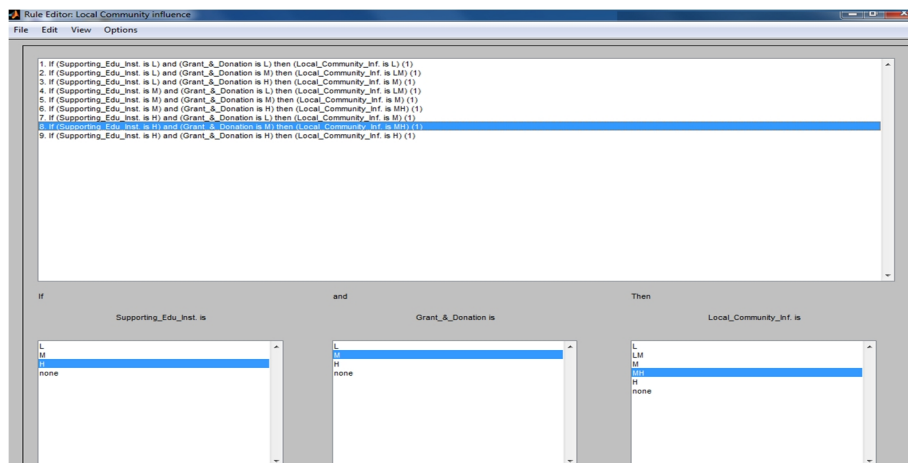

Fig. 9. Suppliers' final scores for each sustainability dimenstion.

6. Fuzzy multi-objective MINLP model for Order allocation (Phase 3)

The information presented in Tables8and9can be utilized for constructing the final fuzzy multi-objective MINLP model corresponding to the case study presented in this research paper. Demand (D) is predicted to be about 420000 units annually. Unit holding cost for planning period (H) is 20% of unit price;minimum acceptance rate of perfect product (η) is 0.95. The model hasnot been presented in this paper due to space limitations, but can be easily constructed based on the information provided in the paper. GAMS 22.1 software was utilized to solve the non-linear programming model

Table 9
Model input data

	Unit price (P_i)	Unit transportation cost (ϕ_i)	Ordering cost (A_i)	Capacity (C_i)	Product perfect rate (η_i)
Supplier S1	2.92	0.15	32	150000	0.96
Supplier S2	2.88	0.02	32	200000	0.95
Supplier S3	3	0.05	32	300000	0.97

The model solving process starts with finding the lower and upper limits of a solution for each objective function in a separate manner. The obtained values which are the positive ideal solutions (best values) and the negative ideal solutions (worst values) of each objective function are tabulated in Table 10. The membership functions are then calculated using Eqs. 3.58 and 3.59. The weights of the four objective functions are set as $W_1 = 0.218$ for cost, $W_2 = 0.337$ for environmental sustainability, $W_3 = 0.166$ for social sustainability, and $W_4 = 0.278$ for economic sustainability objective functions according to experts' opinions using the FAHP approach.

Table10
Positive and negative ideal solutions.

	Z_k^+	Z_k^-	Z_l^+	Z_l^-
Z_1	1249957.220	1228228.905	-	-
Z_2	-	-	315267.126	273521.138
Z_3	-	-	255776.370	214111.294
Z_4	-	-	264172.642	251490.443

7. Results and Sensitivity Analysis

The optimal solution of the proposed model applied for the real-world application is as follows:

$x_1 = 0.2512$, $x_2 = 0.2122$, and $x_3 = 0.5365$ which can be expressed as the percentage of predicted annual demand. Considering 420000 Kg of annual demand by the manufacturer, the allocated amount to supplier S1 is 105504 Kg, 89124 Kg is allocated to supplier S2, and this amount for supplier S3 is 225330 Kg. The optimal value of each objective function together with achievement level of the objective functions are tabulated in Table 11.

Table11
Final order quantities, optimal objective functions for different valuesof objective's weights.

	$W_1 = 0.218$, $W_2 = 0.337$, $W_3 = 0.166$, $W_4 = 0.278$	$W_1 = 0.25$, $W_2 = 0.25$, $W_3 = 0.25$, $W_4 = 0.25$
x_1	105504	119364
x_2	89124	85176
x_3	225330	215460
Z_1	1245220.448	1244525.142
Z_2	287589.536	283957.635
Z_3	240490.763	238471.346
Z_4	256931.836	257649.139
μ_1	0.218	0.500
μ_2	0.337	0.500
μ_3	0.633	0.500
μ_4	0.429	0.500

The sensitivity analysis of the proposed model was conducted without considering the DMs' weights for each objective function. The results are summarized in Table11 and Fig. 10. In the case of different weights, the objective function corresponding to maximization of environmental sustainability was the most important one among the DMs of the manufacturer organization. Their decision can be justified by the comprehensive literature review in Section 2which demonstrates the need for obtaining overall sustainability in industrial operations. This could be arising due to many factors such as stricter regulations related to environment, diminishing non-renewable resources, and increasing consumer preference for environmentally-friendly products. Based on the results obtained in Section 5.4,presented in Table 8 and Fig. 9, the proposed model is suggesting that the order quantity to be allocated to S3 would be the highest as it is the most sustainable supplier. Contrarily, the allocated order to supplier S3 is following a decreasing trend as the weight of environmental sustainability objective function (W_2) decreased significantly from 0.337 to 0.25.

The outcome of the model expressing the allocated order quantity brings up an interesting fact regarding supplier S1; although Supplier S1 is the worst supplier with respect to environmental and social sustainability consideration, the order quantity allocated to it is more than supplier S2 which is the least allocated supplier. Therefore, it can be perceived that still lower finished good price with reasonable quality and on-time delivery is a driving element for the manufacturer organization for allocating more to a supplier (S1). Moreover, increasing W_1 from 0.218 to 0.25 causes an increase in order quantity allocated to supplier S1. This is confirmed by output of the model as the order quantity in weighted min-max model is 105504 Kg and is escalated to 119364 Kg when all the weights are considered equal.

Regarding the optimal value of each objective function, it is worth mentioning that increasing W_1 related to cost minimization objective functionis not leading to an increase in the optimal value of Z_1, but to a reduction of 695.306 in its value. This can be justified by considering the fact that increasing W_1accompanied by a significant decrease in W_2had an effect on decreasing the order quantity allocated to suppliers S2 and S3 as they are more environmentallyfriendly than S1.

Similarly, the same argument can be brought up for the decreasing value of Z_3 which is related to social sustainability maximization. The value of Z_3 decreased by 2019.418 regarding an increase in W_3. As a clarification, the increase in W_3 happened with almost the same decrease in W_2 which is not addressing the reason for the reduction ofZ_3 value yet. But, based on Fig.10, the difference between environmental sustainability scores of S3 and S2 (0.248 and 0.268) ismore than the same difference in social sustainability scores (0.192 and 0.031). Therefore, the increasing trend of Z_3 is accaptable and justified.
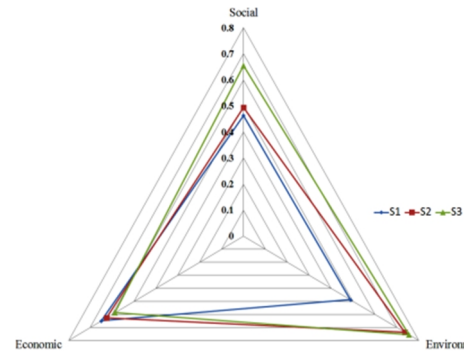

Fig. 10. Sensitivity analysis of order allocations to different values of W_1, W_2, W_3, and W_4.

8. Managerial Implications

This paper presents a real-world application of sustainable supplier selection and order allocation that can bring up a two-fold implication for anyone who is in charge of decision-making in manufacturing organizations. Firstly, the approach presented in Section 3 can be utilized as a road map for suppliers and spare part manufacturers to consistently evaluate themselves rather than be assessed by other large organizations which are seeking for more sustainable suppliers. Fig. 11 can shed light on the problems that suppliers S1, S2, and S3 are dealing with based on analysing each sub criterion score before applying a manufacturer's preference weights obtained using FAHP-QFD. Therefore, these scores can provide concrete measures for DMs and production managers to identify which sub criterion is causing difficulty and needs to be amended and improved. Consequently, the sustainability level can be improved after some redesigns, corrections, renewal studies, and material replacements.

In this research, for instance, local community influencingsub criterion score for S1 is 0.333 which is the lowest among other sub criteria. Local community influence deals with two Ifs:one of them is SEI.SupplierS1 is currently involved in six academic projects in conjunction with local universities and educational institutes (see input data provided in Table 7). During a meeting with the CEO of this company, it was clarified that supplier S1 is not willing to participate inmost of the proposed projects as they are not adding value to the company's manufacturing and supply chain operations. He concluded that they are more interested in participating in a funded research project in which they can gain some profits both monetary and improvements in their production and supply chain activities. Regarding the other social sustainability sub criterion, which is employment practices, three suppliers are following the same trend where supplier S1 is holding the lowest score. Regarding health and safety sub criteria, supplier S2's score is the lowest among the three supplier. This can be justified as supplier S2 is not doing very well on ensuring the safety of their employees. The number of incidents happening every year in their organization is 7.7 that is the highest number among the three suppliers (see Table 7). Although they are practising OHSAS 18001, but still

the manufacturing plant environment needs to be improved regarding health and safety.

As discussed above, suppliers themselves can use the approach presented in this paper to evaluate their own activities regarding implementing sustainability foundations in their organizations. An unsustainable product design usually incurs excessive waste and use of toxic material to the environment resulting in an increase in production and operational costs. In this respect, manufacturing sustainable products becomes a crucial issue for most manufacturing and production managers in order to move towards sustainable manufacturing. Ghadimi et al. (2012, 2013) pointed out that the first step to achieve this goal is to assess the sustainability level of any manufactured product inside the company with a great precision. During a discussion with the production manager of supplier S3 regarding the results of this study, they confirmed the above-mentioned point of view and emphasized that even a small attempt toward sustainable manufacturing leads to more satisfaction of their stakeholders which will eventually result in more investments from them.

Besides, being a more sustainable supplier can increase the organization's opportunity to be selected by downstream manufacturers who are also concentrating on practicing sustainable supply chain. This matter was proven in the real-world application presented in this paper as supplier S3 was allocated about 54% of the whole annual demand required by the manufacturer, because it is more sustainable than the others. Generally, most suppliers' companies are categorized into Small& Medium Enterprises (SMEs) that are striving in the competitive market for more profit, consequently remaining in the business. Therefore, the managerial implication that can be provided forDMs inside SMEs is

that although supplier S3 tolerated more resource consumption regarding spending more money and time for moving towards TBL sustainability approach, ultimately more than half of the downstream manufacturer's demandswereallocated to them, which means more profit and safe margins in today's competitive market.

The proposed approach in this paper has also managerial implications for the bigger manufacturing organizations such as the manufacturer company(buyer) in this current paper in which the project was implemented. As mentioned before in Section 4, the manufacturer in question is striving to adapt itself to the global sustainability directives in order to export its finished products globally all over the globe with the maximum sustainability standards. In other words, they realized that gaining more profit and staying in the business is not possible without producing sustainable products; for example, selling their products in Europe market. Obviously, it is important to export more sustainable products which are completely in compliance with EU directives, such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS), etc., rather than manufacture just cheap products without any sustainability standards. Using the fuzzy QFD approach and capturing customers 'requirements, which are later tied with suppliers evaluation, can help managers to move towards this direction. Furthermore, the proposed order allocation model provides this ability forDMs inside the companies that can regulate the model based on their own preference for allocating orders according to the sustainability objective functions that are actually incorporating sustainable considerations into their decision-making process.
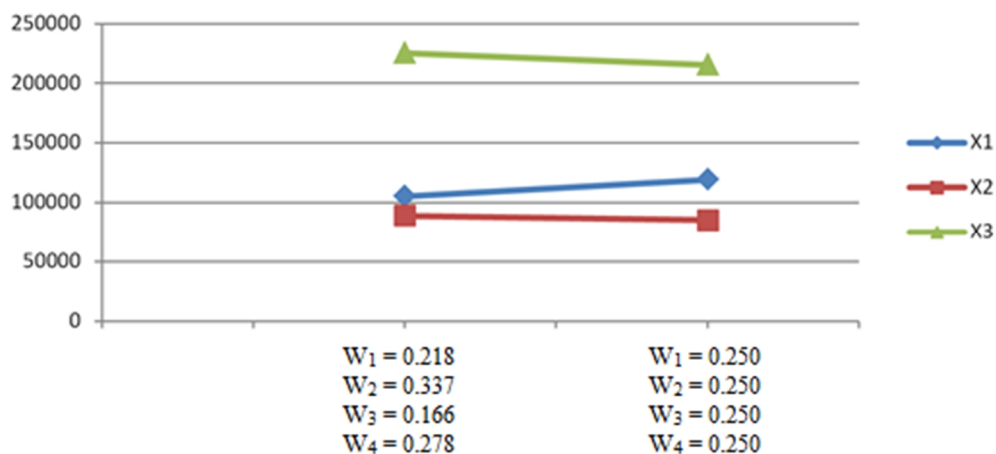

Fig. 11.Comparison of suppliers sub criteria scores

9. Concluding Remarks and Future Works

Environmental and social challenges are mounting and still being considered as an important issue as the availability of ecosystem is threatened by the fast pace of economic development. The applications of sustainability paradigm in supply chain activities are abundantly being

debated among scholars and industrial practitioners. Therefore, solely considering green aspects of sustainability in the supplier selection problem would not be recognized as a comprehensive evaluation of suppliers. This research study attempts to address the sustainable supplier selection problem in conjunction with order allocation problem. A comprehensive literature review

was conducted to capture every possible aspect of green/sustainable supplier selection problem regarding green and sustainable criteria. The proposed approach is followed by an evaluation method that encompasses the FAHP-QFD to identify the manufacturers' requirements and expectations from the supplier in question and formulizes this requirement as preference weights. Thereafter, the FAM is applied to measure each supplier's score regarding three dimensions of sustainability (environment, economic and social). Obtained weights are then incorporated into a fuzzy multi-objective MINLP order allocation model that facilitates the allocation of orders to the suppliers in question. The main contributions of this research activity are briefed as follows:

1) We addressed sustainable supplier selection and order allocation problem based on environmental, economic, and social sustainability dimensions. We aim to bring this important problem under the attention of managers and CEOs of procurement organization in the field of sustainable supply chain and manufacturing.

2) We proposed an efficient integrated FQFAMto solve the sustainable supplier selection problem.

3) Using the scores obtained from the assessment method, a fuzzy multi-objective MINLPwas developed to address the sourcing decisions of a typical manufacturing organization.

Future research activities in this area are to address the problem while dealing with multiple products and multiple buyers. Besides, time dimension also needs to be modelled to capture the demand variability rather than constant demand. Furthermore, nowadays, OEM companies try to establish a long-term relationship with their suppliers rather than constantly changing their suppliers. Investigating further in the buyer-supplier relationships is required to investigate drivers of establishing a long-term relationship between manufacturers and suppliers and address the possible gaps by developing approaches and frameworks to maintain such a relationship using state-of-the-art technologies such as cloud and agent technologies. Moreover, the issues and requirements in the other dyadic relationships of the supply chain, such as manufacturer-retailer, can also be studied and investigated.

Reference

Akman, G. (2014). Evaluating suppliers to include green supplier development programs via Fuzzy c-means and VIKOR methods. *Computers & Industrial Engineering*, 86, 69-82.

Amindoust, A., Ahmed, S., Saghafinia, A. &Bahreininejad, A. (2012). Sustainable supplier selection: Aranking model based on fuzzy inference system. *Applied Soft Computing,* 12(6), 1668-1677.

Ansari, A. &Modarress, B. (1994). Quality function deployment: the role of suppliers. *International Journal of Purchasing and Materials Management,* 30(3), 27-35.

Awasthi, A., Chauhan, S.S. &Goyal, S.K. (2010). A fuzzy multicriteria approach for evaluating environmental performance of suppliers. *International Journal of Production Economics,* 126(2), 370-378.

Azadnia, A. H. (2016). A Multi-Objective Mathematical Model for Sustainable Supplier Selection and Order Lot-Sizing Under Inflation. *International Journal of Engineering-Transactions B: Applications,*29(8), 1141.

Azadnia, A. H., Ghorbani, M., &Arabzad, S. M. (2015b). A Simulation Study on Bullwhip Effect in Supply Chain Based on Theory of Constraint. In: Research Advances in Industrial Engineering (pp. 77-87). Springer International Publishing.

Azadnia, A.H., Ghadimi, P., Mat Saman, M.Z., Wong, K.Y. & Sharif, S. (2011). Supplier Selection: A Hybrid Approach Using ELECTRE and Fuzzy Clustering. Informatics Engineering and Information Science. In: A. AbdManaf, A. Zeki, M. Zamani, S. Chuprat& E. El-Qawasmeh, (Vol. 252, pp. 663-676): Springer Berlin Heidelberg.

Azadnia, A.H., Saman, M.Z.M. & Wong, K.Y. (2015a). Sustainable supplier selection and order lot-sizing: an integrated multi-objective decision-making process. *International Journal of Production Research*, 53(2), 383-408.

Bai, C. &Sarkis, J. (2010). Integrating sustainability into supplier selection with grey system and rough set methodologies. *International Journal of Production Economics,* 124(1), 252-264.

Baskaran, V., Nachiappan, S. &Rahman, S. (2012). Indian textile suppliers' sustainability evaluation using the grey approach. *International Journal of Production Economics*, 135(2), 647-658.

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

Byrne, P.J., Heavey, C., Blake, P. & Liston, P. (2013). A simulation based supply partner selection decision support tool for service provision in Dell. *Computers & Industrial Engineering,* 64(4), 1033-1044.

Carnevalli, J.A. & Miguel, P.C. (2008). Review, analysis and classification of the literature on QFD—Types of research, difficulties and benefits. *International Journal of Production Economics,* 114(2), 737-754.

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

Chang, B., Chang, C.-W. & Wu, C.-H. (2011). Fuzzy DEMATEL method for developing supplier selection criteria. *Expert Systems with Applications,* 38(3), 1850-1858.

Chang, D.-Y. (1996). Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research,* 95(3), 649-655.

Cohen, L. & Cohen, L. (1995). Quality function deployment: how to make QFD work for you: Addison-Wesley Reading, MA.

Dai, J. &Blackhurst, J. (2012). A four-phase AHP–QFD approach for supplier assessment: a sustainability perspective. *International Journal of Production Research*, 50(19), 5474-5490.

Fiksel, J. (2010). Evaluating supply chain sustainability. *Chemical Engineering Progress*, 106(5), 28-38.

Genovese, A., Lenny Koh, S., Bruno, G. & Esposito, E. (2013). Greener supplier selection: state of the art and some empirical evidence. *International Journal of Production Research*(ahead-of-print), 1-19.

Ghadimi, P., Azadnia, A.H., MohdYusof, N. & Mat Saman, M.Z. (2012). A weighted fuzzy approach for product sustainability assessment: a case study in automotive industry. *Journal of Cleaner Production,* 33(0), 10-21.

Ghadimi, P., &Heavey, C. (2014a). MASOS: A multi-agent system simulation framework for sustainable supplier evaluation and order allocation. *Proceedings of the 2014 Winter Simulation Conference*, IEEE Press, 1132-1143.

Ghadimi, P., &Heavey, C. (2014b). Sustainable supplier selection in medical device industry: toward sustainable manufacturing. *Procedia CIRP*, 15, 165-170.

Ghadimi, P., Yusof, N. M., Saman, M. Z. M., & Asadi, M. (2013). Methodologies for measuring sustainability of product/process: a review. *Pertanika Journal of Science and Technology*, 21, 303-326.

Ghadimi, P., Azadnia, A. H., Heavey, C., Dolgui, A., & Can, B. (2016a). A review on the buyer–supplier dyad relationships in sustainable procurement context: past, present and future. *International Journal of Production Research*, 54(5).

Ghadimi, P., Dargi, A., &Heavey, C. (2016b). Making sustainable sourcing decisions: practical evidence from the automotive industry. *International Journal of Logistics Research and Applications*, 1-25.

Ghadimi, P., Dargi A., Heavey C. (2017). Sustainable supplier performance scoring using audition check-list based fuzzy inference system: a case application in automotive spare part industry.*Computers & Industrial Engineering*,DOI: 10.1016/j.cie.2017.01.002.

Ghodsypour, S.H. & O'Brien, C. (2001). The total cost of logistics in supplier selection, under conditions of multiple sourcing, multiple criteria and capacity constraint. *International Journal of Production Economics,* 73(1), 15-27.

Girubha, J., Vinodh, S., & KEK, V. (2016). Application of Interpretative Structural Modelling integrated Multi Criteria Decision Making methods for sustainable supplier selection. *Journal of Modelling in Management*, 11(2).

Ho, W., Xu, X. &Dey, P.K. (2010). Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. *European Journal of Operational Research,* 202(1), 16-24.

Hsu, C.-W., Kuo, T.-C., Chen, S.-H. & Hu, A.H. (2013). Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. *Journal of Cleaner Production,* 56(0), 164-172.

Kumar, A., Jain, V. & Kumar, S. (2014). A comprehensive environment friendly approach for supplier selection. *Omega,* 42(1), 109-123.

Kuo, R.J., Wang, Y.C. &Tien, F.C. (2010). Integration of artificial neural network and MADA methods for green supplier selection. *Journal of Cleaner Production,* 18(12), 1161-1170.

Lin, C.-C. (2004). A weighted max–min model for fuzzy goal programming. *Fuzzy sets and systems,* 142(3), 407-420.

Mafakheri, F., Breton, M. &Ghoniem, A. (2011). Supplier selection-order allocation: A two-stage multiple criteria dynamic programming approach. *International Journal of Production Economics.*

Makui, A., Gholamian, M. R., &Mohammadi, E. (2016). A hybrid intuitionistic fuzzy multi-criteria group decision making approach for supplier selection.*Journal of Optimization in Industrial Engineering*, 9(20), 61-73.

Mehregan, M.R., Chaghooshi, A.J. and Hashemi, S.H., 2014. Analysis of sustainability drivers among suppliers of Iranian Gas Engineering and Development Company. *International Journal of Applied Decision Sciences*, 7(4), pp.437-455.

Neumüller, C., Lasch, R., & Kellner, F. (2016). Integrating sustainability into strategic supplier portfolio selection. *Management Decision*, 54(1), 194-221.

Özgen, D., Önüt, S., Gülsün, B., Tuzkaya, U.R. &Tuzkaya, G. (2008). A two-phase possibilistic linear programming methodology for multi-objective supplier evaluation and order allocation problems. *Information Sciences,* 178(2), 485-500.

Plastics Europe ELCD Data set version 3.0, 1996. Nylon 6 granulate (PA 6); production mix, at plant. Accessed June 2014.

Plastics Europe ELCD Data set version 3.0, 1998. Polyvinyl chloride; production mix, at plant. Accessed June 2014.

Plastics Europe ELCD Data set version 3.0, 1999. Polyethylene low density granulate (PE-LD); production mix, at plant. Accessed June 2014.

Shabanpour, H., Yousefi, S., &Saen, R. F. (2017). Future planning for benchmarking and ranking sustainable suppliers using goal programming and robust double frontiers DEA. *Transportation Research Part D: Transport and Environment*, 50, 129-143.

Sikdar, S.K. (2012). Measuring sustainability. *Clean Technologies and Environmental Policy,* 14(2), 153-154.

Tavana, M., Yazdani, M., & Di Caprio, D. (2016). An application of an integrated ANP–QFD framework for sustainable supplier selection. *International Journal of Logistics Research and Applications*, 1-22.

Veleva, V., Hart, M., Greiner, T. &Crumbley, C. (2003). Indicators for measuring environmental

sustainability: A case study of the pharmaceutical industry. *Benchmarking: An International Journal,* 10(2), 107-119.

Wang, C. H. (2015). Using quality function deployment to conduct vendor assessment and supplier recommendation for business-intelligence systems. *Computers & Industrial Engineering*, 84, 24-31.

Weber, C.A. & Current, J.R. (1993). A multi-objective approach to vendor selection. *European Journal of Operational Research,* 68(2), 173-184.

Xu, J. & Ding, C. (2011). A class of chance constrained multi-objective linear programming with birandom coefficients and its application to vendors selection. *International Journal of Production Economics,* 131(2), 709-720.

Zhang, F., Yang, M. & Liu, W. (2014). Using integrated quality function deployment and theory of innovation problem solving approach for ergonomic product design. *Computers & Industrial Engineering,* 76(0), 60-74.

Zimmer, K., Fröhling, M., & Schultmann, F. (2016). Sustainable supplier management–a review of models supporting sustainable supplier selection, monitoring and development. *International Journal of Production Research*, 1-31.

Zimmermann, H.J. (1978). Fuzzy programming and linear programming with several objective functions. *Fuzzy sets and systems,* 1(1), 45-55.