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Article *in* International Journal of Production Research · January 2015

DOI: 10.1080/00207543.2014.935827

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International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tprs20

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Published online: 17 Jul 2014.

International Journal of Production Research, 2015
Vol. 53, No. 2, 383–408, http://dx.doi.org/10.1080/00207543.2014.935827

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(*Received 19 July 2013; accepted 11 June 2014*)

Within supply chains activities, selecting appropriate suppliers based on the sustainability criteria (economic, environmental and social) can help companies move toward sustainable development. Although several studies have recently been accomplished to incorporate sustainability criteria into supplier selection problem, much less attention has been devoted to developing a comprehensive mathematical model that allocates the optimal quantities of orders to suppliers considering lot-sizing problems. In this research, we propose an integrated approach of rule-based weighted fuzzy method, fuzzy analytical hierarchy process and multi-objective mathematical programming for sustainable supplier selection and order allocation combined with multi-period multi-product lot-sizing problem. The mathematical programming model consists of four objective functions which are minimising total cost, maximising total social score, maximising total environmental score and maximising total economic qualitative score. The proposed model is developed based on the parameters achieved through the preprocessing of suppliers' social, environmental and economic data by a rule-based weighted fuzzy approach and fuzzy analytical hierarchy process. The proficiency and applicability of the proposed approach is illustrated by a case study of packaging films in food industry. Considering sustainability criteria in the proposed model reveals that a higher value of sustainable purchasing is achievable in comparison with a single-objective cost-based model.

Keywords: sustainable supplier selection; order allocation; lot-sizing; fuzzy logic; fuzzy analytical hierarchy process; multi-objective decision-making

1. Introduction

In the competitive environment of the global market, there has been a steady increase in the outsourcing of raw materials, components and services to suppliers. Therefore, within new strategies for procuring and manufacturing, the vital role of suppliers has been highlighted for obtaining corporate competitive edge and enhancing a company's performance (Sucky 2007). Accordingly, supplier selection has become a strategic decision in the field of supply chain management (SCM) (Azadnia et al. 2011). Integration of lot-sizing models (as well-known problems in the production and inventory management literature developed by Wagner and Whitin (1958)) and supplier selection has recently achieved great attention among researchers. Several research activities in this field (Basnet and Leung 2005; Aissaoui, Haouari, and Hassini 2007; Dai and Qi 2007; Hassini 2008; Ustun and Demirtas 2008; Ebrahim, Razmi, and Haleh 2009; Keskin, Melouk, and Meyer 2010; Rezaei and Davoodi 2011; Woarawichai, Kullpattaranirun, and Rungreunganun 2011; Sawik 2011; Hammami, Frein, and Hadj-Alouane 2012; Rezaei and Salimi 2012) study the situation where buyers need to determine the optimal quantity of products to order in each period from each supplier to meet the requirements of production plan while satisfying given constraints. In these research activities, some objective functions such as total cost (purchasing, inventory, ordering and transportation), quality and service level have been formulated for the optimisation purposes together or separately.

By the emergence of sustainability during past decades, there has been an increasing interest among practitioners and academia in the field of sustainable supply chain management (Carter and Rogers 2008; Amindoust et al. 2012). Companies have been motivated to modify their supply chains activities based on sustainability issues to enhance their overall sustainability level in order to fulfil more demanding environmental and social legislation and to deal with the increasing market forces from different stakeholder groups (Govindan, Khodaverdi, and Jafarian 2013). Traditionally, the process of supplier selection is mainly influenced by different intangible and tangible criteria such as price, quality,

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This article was originally published with errors. This version has been corrected. Please see Erratum (http://dx.doi.org/10.1080/00207543.2014.950450)

technical capability, delivery performance, etc. (Önüt, Kara, and Işik 2009; Friedl and Wagner 2012). Further thoughts show that cooperation with environmentally, socially and economically potent suppliers can improve the performance of the supply chain in terms of sustainability in order to move toward sustainable development (Büyüközkan and Çifçi 2012). Therefore, many organisations have recently focused on incorporating environmental, social and economic aspects of sustainability in supplier selection processes resulting from the adoption of sustainable supply chain initiatives (Govindan, Khodaverdi, and Jafarian 2013; Seuring and Müller 2008).

The sustainable supplier selection problem can be defined as a classical supplier selection problem in which environmental and social criteria are taken into account to select and monitor suppliers' performances (Genovese et al. 2010). Most studies in this field have only focused on the economic and environmental aspects of sustainability (Handfield et al. 2002; Lu, Wu, and Kuo 2007; Kannan et al. 2008; Lee et al. 2009; Hsu and Hu 2009; Kannan, Pokharel, and Sasi Kumar 2009; Yeh and Chuang 2011; Büyüközkan and Çifçi 2012; Fu, Zhu, and Sarkis 2012; Shaw et al. 2012; Shen et al. 2013). In recent years, few researchers have tried to incorporate the social facet of sustainability separately or together with economic and environmental aspects in the problem of supplier selection (Kuo, Wang, and Tien 2010; Bai and Sarkis 2010b; Punniyamoorthy, Mathiyalagan, and Parthiban 2011; Govindan, Khodaverdi, and Jafarian 2013). However, there are still very limited research activities in the literature of sustainable supplier selection that consider sustainability issues in the integrated problem of multi-period multi-product lot-sizing and supplier selection.

Based on our rigorous literature review, few research activities have been done which consider economic, environmental and social criteria together for supplier selection. It can be perceived that the focus on sustainability issues in supplier selection and order allocation problem in the corporate practice is at an early stage. Moreover, as shown in the Table 1, far too little attention has been paid to developing comprehensive frameworks and practical mathematical models for order allocation to suppliers that consider sustainability issues in the integrated problem of supplier selection and order lot-sizing. In addition, most of the studies in the field of green and sustainable supplier selection and order allocation have introduced hypothetical examples rather than providing a real-world application. This issue is always considered by the author themselves as one of the biggest limitations of this area of study (Genovese et al. 2013;

Table 1. Literature on green/sustainable supplier selection.

Author	Solution approach	Economic	Environ-mental	Social	Order allocation
Handfield et al. (2002)	AHP		✓		
Humphreys et al. (2006)	Fuzzy logic	✓	✓		
Lee et al. (2009)	Multi-objective decision analysis		✓		✓
Tsai and Hung (2009)	Multi-objective programming	✓	✓		✓
Lee et al. (2009)	FAHP	✓	✓		
Hsu and Hu (2009)	ANP	✓	✓		
Awasthi Chauhan, and Goyal (2010)	FTOPSIS		✓		
Keskin Melouk, and Meyer (2010)	ANN-MADA	✓	✓		
Bai and Sarkis (2010a)	Rough set theory	✓	✓		
Bai and Sarkis (2010b)	Rough set theory and grey system	✓	✓	✓	
Chen et al. (2010)	Fuzzy logic	✓	✓		
Choy et al. (2004)	AHP–QFD	✓	✓	✓	
Ng (2008)	Structural equation modelling and FAHP	✓	✓	✓	
Rezaei and Davoodi (2011)	Multiple attribute utility	✓	✓	✓	
Hsu et al. (2013)	DEMATEL	✓	✓		
Yeh and Chuang (2011)	Multi-objective GA	✓	✓		✓
Bayrak et al. (2007)	DEMATEL, FANP and FTOPSIS	✓	✓		
Shen et al. (2013)	FTOPSIS		✓		
Zhang et al. (2013)	Multi-objective programming and GA	✓	✓		✓
Amindoust et al. (2012)	Fuzzy inference	✓	✓	✓	
Friedl and Wagner (2012)	Grey-based DEMATEL	✓	✓		
Shaw et al. (2012)	FAHP and Multi-objective programming	✓	✓		
Bai and Sarkis (2010b)	Grey approach		✓	✓	
Govindan, Khodaverdi, and Jafarian (2013)	FTOPSIS	✓	✓	✓	
Kannan et al. (2013)	FAHP, FTOPSIS, and multi-objective programming	✓	✓		✓
Kannan et al. (2008)	DEA	✓	✓		

Govindan, Khodaverdi, and Jafarian 2013). Therefore, in order to address the above-mentioned problems, a comprehensive multi-objective decision-making process for the integrated problem of sustainable supplier selection and multi-period lot-sizing problem is developed. In addition, a case study is presented in order to show the applicability of the proposed model and framework.

The rest of this paper is organised as follows: in Section 2, a comprehensive literature review which includes sustainable supplier selection and order allocation and related criteria is given. Subsequently, a detailed explanation of the proposed model and framework are presented in Section 3 and is followed by Section 4 in which the case study is briefly introduced. Next, results and discussions of our study are detailed in Section 5. Section 6 belongs to managerial implications. Finally, in Section 7, conclusions are presented.

2. Literature review

2.1 *Supplier selection and order allocation*

Supplier selection is a multi-criteria decision-making problem and there are many approaches in order to deal with the problem of supplier selection and order allocation in the literature which include linear programming (LP) (Ng 2008), mixed-integer non-linear programming (MINLP) (Rezaei and Davoodi 2012), analytic network process (ANP) (Lin et al. 2010; Tseng, Chiang, and Lan 2009), Data Envelopment Analysis (DEA) (Wu and Blackhurst 2009; Kuo, Lee, and Hu 2010), multiple-objective programming (MOP) (Lin 2012; Haleh and Hamidi 2011; Wu et al. 2009), analytic hierarchy process (AHP) (Chan and Kumar 2007), genetic algorithm (GA) (Ding, Benyoucef, and Xie 2005; Sadeghieh et al. 2011), techniques for order preference by similarity to ideal solution (TOPSIS) (Awasthi, Chauhan, and Goyal 2010), fuzzy approaches (Bayrak, Çelebi, and Taşkin 2007; Pitchipoo, Venkumar, and Rajakarunakaran 2013) and elimination and choice expressing reality (ELECTRE) (Azadnia et al. 2011). Ho, Xu, and Dey (2010) on their literature review categorised supplier selection approaches into two individual approaches and integrated approaches based on the 78 journal articles published from 2000 to 2008. According to their work, the most frequently used individual approach is DEA, followed by mathematical programming and AHP, and the integrated AHP-Goal programming approaches are more common for integrated approaches. In another study, Chai, Liu, and Ngai (2013) provided a systematic literature review of different decision-making (DM) approach for supplier selection problem based on the papers published from 2008 to 2012. In their research, 26 DM approaches were classified into three main categories: (1) MCDM techniques such as AHP, ANP, ELECTRE and TOPSIS (2) Mathematical programming (MP) techniques DEA, LP, nonlinear programming (NLP), MOP, GP and stochastic programming (3) Artificial intelligence (AI) techniques such as GA and neural network (NN). Also, it was indicated that AHP, LP, TOPSIS and MOP are the most used techniques for supplier selection and order allocation problem.

2.2 *Supplier selection and lot-sizing*

Recently, researchers have shown an increased interest in the integrated problem of supplier selection and lot-sizing. Combination of supplier selection and lot-sizing for allocating orders to suppliers over the time planning horizon can significantly reduce costs (Aissaoui, Haouari, and Hassini 2007). Several studies have been carried out in order to combine supplier selection and multi-period order lot-sizing to determine the optimal order quantities in each period. Basnet and Leung (2005) presented an uncapacitated mixed integer model for a multi-period inventory lot-sizing scenario where there are multiple products and multiple suppliers. A supplier selection problem integrated with resource-constrained single product, multi-period and inventory lot-sizing problem price discounts schemes was proposed by Hassini (2008). They proposed a single-objective cost-based model. Sadeghi Moghadam, Afshar, and Sohrabi (2008) proposed an integrated intelligence algorithm for multi-period multi-product lot-sizng with supplier selection considering multiple-echelon inventory system. In their research, a hybrid model of fuzzy neural network was used for demand forecasting. Ustun and Demirtas (2008) developed an integrated model of ANP and achievement scalarising functions in order to solve supplier selection problem integrated with multi-period inventory lot-sizing. A multi-period goal programming model including total cost, total defect rate and total value of purchasing objective functions was developed in order to determine the optimum quantities of orders and inventory levels in each period. Ebrahim, Razmi, and Haleh (2009) introduced a multi-objective integer programming model in which qualitative and quantitative factors are considered. They defined defective items, late delivered items and total weighted quantity of purchasing as the objective functions of the multi-objective model and solved the model using a scatter search algorithm (SSA). Woarawichai, Kullpattaranirun, and Rungreunganun (2011) proposed a single-objective model for multi-period multi-product lot-sizng with supplier selection under storage space and budget constraints and solved the model using LINGO software. Rezaei and Davoodi (2011) proposed two multi-objective mixed integer non-linear models for multi-period multi-product lot-sizing with supplier selection problem and solve the models using GA. Cost, quality and service level were defined as the main objective functions of the models. Hammami, Frein, and Hadj-Alouane (2012) proposed a mathematical model in order to deal with supplier selection problem integrated with multi-period multi-product lot-sizing in an international environment with the objective of minimising the total cost.

2.3 *Sustainable supplier selection, criteria, approaches*

Sustainable development and sustainability is frequently interpreted as a synthesis of economic, environmental and social development, a triple-bottomline approach (Dai and Blackhurst 2011; Gauthier 2005). As the concept of sustainability has become a key factor in supply chain management, companies try to incorporate sustainability elements on their supply chain functions in order to maintain their competitive edge. Hence, social and environmental elements should be incorporated in supplier selection processes besides traditional cost and economic elements. A review of criteria for supplier selection from a sustainable perspective is given in the next sections.

2.3.1 *Economic criteria*

Economic criteria have been considered for evaluating the suppliers in traditional supplier selection approaches. Several studies have been carried out in order to identify the main criteria for supplier selection problem. According to a research conducted by Dickson (1966), 23 criteria such as product quality, on-time delivery and performance history of suppliers were identified for supplier selection problem. Later, based on the literature survey accomplished by Weber, Current, and Benton (1991) that reviewed 74 research papers published between 1966 and 1990, it was revealed that price, delivery performance, quality and technical capability are the most important factors to be considered in solving the problem of supplier selection. The results of the research accomplished by Ho, Xu, and Dey (2010) revealed that delivery, price and cost are the most used criteria for evaluating the performance of suppliers.

2.3.2 *Environmental criteria*

Considering the impact of industrial productions on the environment, many companies are now undertaking environmental initiatives to improve the environmental performance of their supply chain functions. Hence, assessment of environmental performance of suppliers has been highlighted. Companies have tried to motivate their suppliers to enhance their environmental performance by making environmental requirements. Several researches have been carried out in the literature in order to summarise the environmental factors and approaches for supplier evaluation. For example, Handfield et al. (2002) evaluated the suppliers using AHP based on environmental criteria such as waste management, packaging/reverse logistic, environmental certificates and environmental friendly product design. Hsu and Hu (2009) developed a new model for selecting suppliers with emphasis on hazardous substance management (HSM) issues based on ANP. In their research, several environmental criteria such as environmental management system (EMS), hazardous substance management system, capability of green design criteria and Green materials coding and recording have been used for evaluating the suppliers. Yeh and Chuang (2011) tried to incorporate green criteria including environmental performance assessment, green image, green design, green supply chain management, product recycling and pollution treatment cost for solving supplier selection and production volumes transportation problems. They proposed two multi-objective models for solving the problem. A study has been conducted by Shaw et al. (2012) in order to develop low carbon supply chain by solving the supplier selection problem. A combined approach of fuzzy-AHP and fuzzy multi-objective linear programming has been developed in their research. They offered greenhouse gas emission, cost, quality, lead time and demand criteria for supplier selection and order allocation problem. Kannan et al. (2013) proposed a multi-objective programming approach for supplier selection and order allocation in a green supply chain. In their study, environmental criteria were determined as pollution production, resource consumption, eco-design and environmental management system.

2.3.3 *Social criteria*

Most studies in the field of sustainable supplier selection focused on environmental and economic aspects of sustainability. Recently, due to increased pressure from government and different types of stakeholders for incorporating social responsibility issues in supply chain activities, few researchers have tried to incorporate social responsibility dimensions in supplier selection problem (Azadnia et al. 2013; Amindoust et al. 2012). Bai and Sarkis (2010b) categorised social metrics for supplier selection decision into two main criteria: (1) Internal social criteria including employment practices and safety factors (2) External social criteria including local communities influence, contractual stakeholders influence and other stakeholders influence. Rough set theory and grey system was used in their research to analyse the data. Punniyamoorthy, Mathiyalagan, and Parthiban (2011) incorporated safety and social environmental criteria for supplier performance evaluation. In another study, Amindoust et al. (2012) developed a model for sustainable supplier selection problem using ranking model based on fuzzy inference system considering all three dimensions of sustainability. However, they did not illustrate their proposed approach by a real case study. Azadnia et al. (2012) considered occupational health and safety management systems and the rights of stakeholders as the social criteria besides economic and environmental criteria for supplier selection problem. They proposed an integrated approach of self-organising map (SOM) and multi-criteria decision-making MCDM methods. Govindan, Khodaverdi, and Jafarian (2013) in their research used employment practices, health and safety, local community influences, and contractual stakeholders influence as the social criteria for supplier selection problem. They used fuzzy multi-criteria decision-making approaches for supplier evaluation and selection. As they mentioned, the lack of a real-life case study for examining their proposed approach was one of their limitations.

3. Proposed framework

In this section, the proposed framework of this study is illuminated by explaining each step. The proposed framework of this research is shown in Figure 1. The approach shows how the sustainability issues can be integrated in the problem of multi-period multi-product lot-sizing with supplier selection.in order to have more sustainable purchasing.

The steps of the proposed framework are listed as follows:

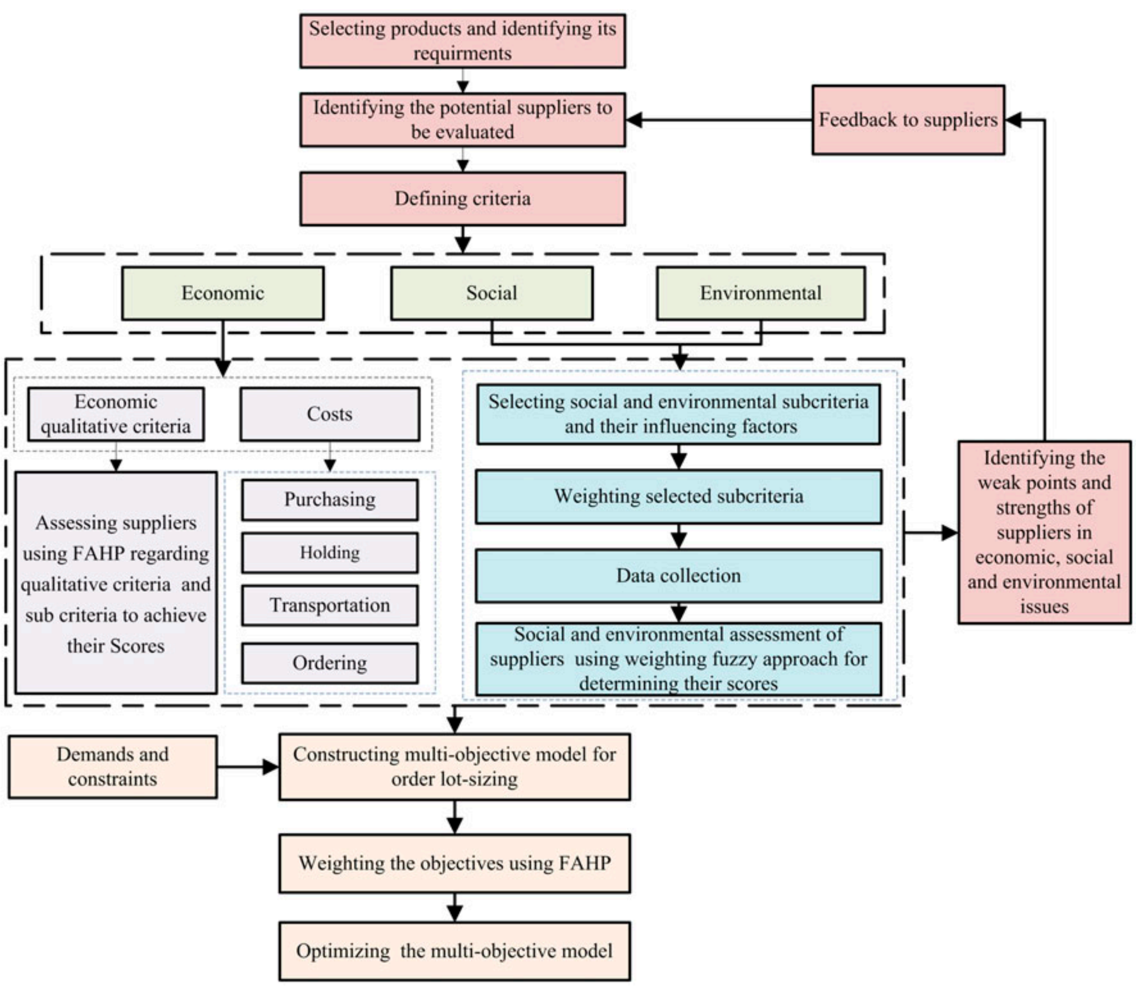

Figure 1. Proposed framework.

(1) Selecting products to be ordered.
(2) Identifying potential suppliers for the products.
(3) Determining appropriate criteria, subcriteria and influencing factors to evaluate the suppliers.
(4) Assessing the suppliers regarding the social and environmental criteria using weighted fuzzy approach.
(5) Assessing the suppliers regarding the economic qualitative criteria using FAHP.
(6) Constructing a multi-objective model for order allocation.

A detailed description of each step is described as follows:

Step 1 encompasses selecting specific products or components to be purchased during the time horizon.
Step 2 is about identifying potential suppliers that produce the selected products and components for the company. The suppliers must provide the data which are needed for evaluation.
Step 3 is involved with selecting all criteria, subcriteria and their influencing factors in order to evaluate suppliers for the selected products. These criteria and subcriteria are selected based on the previous research activities existing in the literature and a validation process which is performed by company's experts. In this step, sustainable criteria are considered besides the traditional criteria of supplier selection. As shown in Figure 1, we defined the social and environmental criteria beside the economic criterion. The economic criterion is divided into two subcriteria including cost (Purchasing, holding, transportation and ordering) and qualitative criteria (after sales service, loyalty and technical capability).
Step 4 talks about supplier evaluation regarding social and environmental criteria. In this step, a rule-based weighted fuzzy approach is proposed for supplier evaluation. As shown in Figure 2, firstly, all of the social and environmental data are transferred into grades of membership as the fuzzy set of inputs. Afterward, the target value is defined for each input variable. These values show the minimum and maximum values of the input variables. For constructing the output membership function, the target range is set between zero and one as the worst and the best values for each criterion, respectively. The construction of input and output variables is followed by the main part of fuzzy approach which is fuzzy rule construction. The fuzzy 'if–then' rules are defined according to the experts' knowledge of the company. Afterward, these rules are used by fuzzy inference system in order to learn how to transform a set of inputs to corresponding outputs. Then, defuzzification process comes up to change the results to a crisp value. In order to run the fuzzy evaluation, MATLAB fuzzy logic toolbox is employed. Finally, the score of each supplier in each sustainability criterion is calculated using Equation (1).

$$\psi_j = \sum_i w_{ij}\psi_{ij} \tag{1}$$

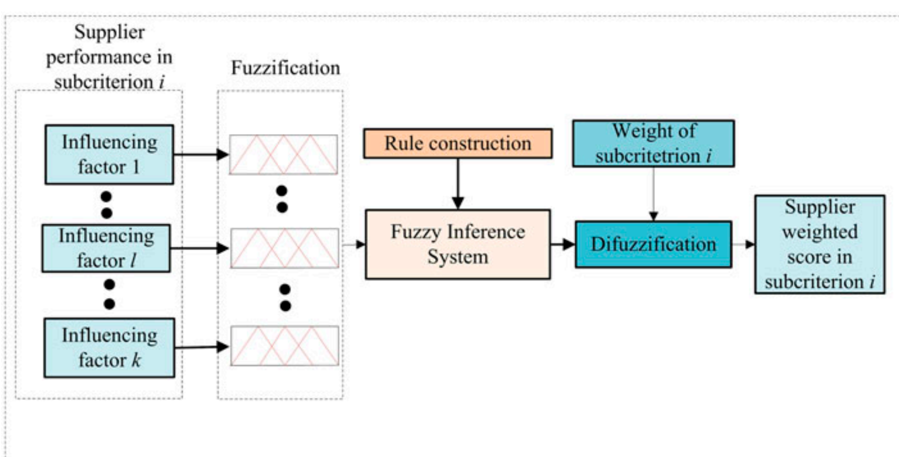

Figure 2. Fuzzy assessment.

where, i shows the index of sustainability subcriteria, j represents the index of sustainability criteria, ψ_j is the score of supplier in jth sustainability criterion, w_{ij} is the weight of ith sustainability subcriterion of jth sustainability criterion and ψ_{ij} stipulates the score of ith sustainability subcriterion of jth sustainability criterion. It is worth mentioning that the weight of each subcriterion is calculated using fuzzy analytical hierarchy process (FAHP) proposed by Chang (1996). Owing to limited space the steps of FAHP are not described in this paper. Readers can refer to Ghadimi et al. (2012) for a comprehensive explanation of Chang's (1996) FAHP.

Step 5 deals with the assessment of suppliers in terms of economical qualitative criteria such as after sales service, loyalty, financial structure and technical capability. FAHP is used to evaluate the suppliers regarding these criteria. The suppliers are assessed based on experts' opinions.

Step 6 is about developing a multi-objective programming model to solve sustainable supplier selection problem integrated with order lot-sizing .This multi-objective function model is aimed to determine the quantity of orders which should be allocated to each supplier in each period, in order to minimise the cost (inventory, purchasing, ordering and transportation cost), maximise the total score of all suppliers in terms of social and environmental issues and maximise the overall score of suppliers in terms of economical qualitative criteria. The inventory level at the beginning and end of the horizon is considered zero. A detailed explanation of the proposed model is described as follows:

Notations

I	Number of products;
J	Number of suppliers
T	Number of periods
D_{it}	Demand of product i at time t
P_{ij}	Price of product i from supplier j
O_j	Ordering cost of supplier j
φ_j	Transportation cost from supplier j per kg
H_i	Holding cost of product i
C_{ij}	Supplier j capacity for product i
V_i	Storage space needed for product i
S	Maximum storage space
E_{ij}	Score of supplier j for product i in environmental criteria
τ_{ij}	Score of supplier j for product i in social criteria
ω_{ij}	Score of supplier j for product i in economic qualitative criteria
x_{ijt}	Number of product i purchased from supplier j at time t
Y_{jt}	Binary variable 1, if an order allocated to supplier j at time t, otherwise 0

3.1 *Objective functions*

3.1.1 *Total cost*

Based on this objective function, the sum of purchasing cost, ordering cost, holding cost and transportation cost over the time horizon should be minimised.

$$\text{Min } z_1 = \sum_i \sum_j \sum_t x_{ijt} \cdot p_{ij} + \sum_j \sum_t O_j \cdot Y_{jt} + \sum_i \sum_t H_i \left(\sum_j \sum_{k=1}^{t} x_{ijk} - \sum_{k=1}^{t} D_{ik} \right) + \sum_i \sum_j \sum_t x_{ijt} \cdot \varphi_j \qquad (2)$$

3.1.2 *Total economical qualitative score*

In this objective function, the score of each supplier (ω_{ij}) in economical qualitative criteria which is calculated by FAHP are used as a coefficient for x_{ijt}. So, the following objective function is designed to maximise the total economical qualitative score:

$$\text{Max}\, z_2 = \sum_i \sum_j \sum_t x_{ijt} \cdot \omega_{ij} \tag{3}$$

3.1.3 *Total environmental score*

This objective function is aimed to maximise the total environmental score of suppliers. As E_{ij} and x_{ijt} denote Suppliers' scores in environmental criteria calculated by the weighted fuzzy approach and number of product i to allocate to supplier j in period t, respectively, therefore:

$$\text{Max}\, z_3 = \sum_i \sum_j \sum_t x_{ijt} \cdot E_{ij} \tag{4}$$

3.1.4 *Total social score*

This objective function is designed to maximise the total social score of suppliers. Suppliers' scores in social criteria (τ_{ij}) which is calculated by the weighted fuzzy approach are used as coefficient for x_{ijt} in this objective function. So:

$$\text{Max}\, z_4 = \sum_i \sum_j \sum_t x_{ijt} \cdot \tau_{ij} \tag{5}$$

3.2 *Constraints*

3.2.1 *Demand constraint*

The demand constraint requires that all of the demand from buyers for each product should be met in each period. So, it can be formulated as follows (Basnet and Leung 2005):

$$\sum_j \sum_{k=1}^{t} x_{ijk} - \sum_{k=1}^{t} D_{ik} \geqslant 0, \quad \forall i \in I. \tag{6}$$

3.2.2 *Capacity constraint*

This constraint guarantees that the number of products i ordered from supplier j in period t should be equal to or less than the supplier's capacity at that time. Therefore:

$$x_{ijt} \leqslant C_{ij}, \quad \forall i \in I,\ \forall j \in J,\ \forall t \in T \tag{7}$$

3.2.3 *Charging ordering cost constraint*

Based on this constraint, we cannot have an order without charging an appropriate transaction cost. This constraint is given by:

$$\left(\sum_{k=t}^{T} D_{ik} \right) \cdot Y_{jt} - x_{ijt} \geqslant 0, \quad \forall i \in I, \forall j \in J, \forall t \in T \tag{8}$$

3.2.4 *Storage capacity constraint*

This constraint says that there is limited capacity for buyers in each period. The storage constraint is given by (Woarawichai, Kullpattaranirun, and Rungreunganun 2011):

$$\sum_i V_i \cdot \left(\sum_j \sum_{k=1}^{t} x_{ijk} - \sum_{k=1}^{t} D_{ik} \right) \leqslant S \tag{9}$$

3.2.5 *End of horizon inventory level constraint*

This constraint stipulates that the inventory level of each product at the end of the time horizon should be zero.

$$\left(\sum_j \sum_{t=1}^{T} x_{ijt} - \sum_{t=1}^{T} D_{it} \right) = 0, \text{ for all } i \tag{10}$$

3.2.6 *Binary and non-negativity constraints*

$$x_{ijt} \geqslant 0, \quad Y_{jt} = 0, 1 \tag{11}$$

The final multi-objective model seems as follows:

$$\text{Min}\, z_1 = \sum_i \sum_j \sum_t x_{ijt}.p_{ij} + \sum_j \sum_t O_j.Y_{jt} + \sum_i \sum_t H_i \left(\sum_j \sum_{k=1}^{t} x_{ijk} - \sum_{k=1}^{t} D_{ik} \right) + \sum_i \sum_j \sum_t x_{ijt}.\varphi_j \tag{12}$$

$$\text{Max}\, z_2 = \sum_i \sum_j \sum_t x_{ijt}.\omega_{ij} \tag{13}$$

$$\text{Max}\, z_3 = \sum_i \sum_j \sum_t x_{ijt}.E_{ij} \tag{14}$$

$$\text{Max}\, z_4 = \sum_i \sum_j \sum_t x_{ijt}.\tau_{ij} \tag{15}$$

Subject to

$$\sum_j \sum_{k=1}^{t} x_{ijk} - \sum_{k=1}^{t} D_{ik} \geqslant 0, \quad \forall i \in I \tag{16}$$

$$x_{ijt} \leqslant C_{ij}, \quad \forall i \in I, \ \forall j \in J, \ \forall t \in T \tag{17}$$

$$\left(\sum_{k=t}^{T} D_{ik} \right) \cdot Y_{jt} - x_{ijt} \geqslant 0, \quad \forall i \in I, \ \forall j \in J, \ \forall t \in T \tag{18}$$

$$\sum_i V_i \left(\sum_j \sum_{k=1}^{t} x_{ijk} - \sum_{k=1}^{t} D_{ik} \right) \leqslant S \tag{19}$$

$$\left(\sum_{j} \sum_{t=1}^{T} x_{ijt} - \sum_{t=1}^{T} D_{it} \right) = 0, \text{ all } i \tag{20}$$

$$x_{ijt} \geqslant 0 \tag{21}$$

$$Y_{jt} = 0, 1 \tag{22}$$

4. Case study

The packaging industry is the largest recipient of plastic (about 38% of the total production of plastics) (Plastics Europe 2000). Each year the consumption of packaging materials increases and is estimated to rise from 5% to 7% per annum. Among different types of packaging films, multi-layer films are used in a large scale for packaging of food products due to their special characteristics such as good mechanical properties, good sealability and high barrier for water vapour and gases. Due to high consumption rate of multi-layer films in food industries, cooperation with the suppliers of these kinds of packaging films that consider sustainability concerns on their activities and processes can help food manufacturing companies to improve their sustainability degree through their supply chains. Therefore, food manufacturing companies need to implement systematic approaches to evaluate their suppliers based on all three dimensions of sustainability. Moreover, since packaging films are largely used in food companies during a planning horizon, integrating multi-period lot-sizing problem with supplier selection can lead to more efficient procurement plans.

In order to show the proficiency and the practicality of the proposed approach, a case study of packaging film in a food industry has been carried out. The company is one of the the largest and most reputable manufacturers of meat products in Iran and one of the relatively well-known companies in the world. The company's management board decided to consider and incorporate sustainability issues in its whole supply networks in order to maintain their competitive edge. Initially, the managers and executives of the company agreed to assess their suppliers regarding the components that were being provided based on sustainability issues. Moreover, they were interested in determining the optimal-order quantities for allocating to suppliers considering order lot-sizing problem while sustainability issues are taken into account. For this case study, three types of packaging film which were used for packaging ready foods were selected as the sample components to be examined. These three kinds of packaging film are different in terms of size and demand because they are used for packaging different kinds of foods. The main materials which are used for the manufacturing of these packaging films are Linear Low Density Polyethylene (LLDPE) and Polyamide 6 (PA 6).

The decision has been made due to high demand rate of these kinds of packaging films in their production system. It is worth mentioning that this company purchases tonnes of packaging films in different types from its suppliers for the variety of products that are being manufactured annually. Therefore, purchasing these kinds of packaging films from the suppliers that incorporate sustainability issues in their manufacturing processes could help the company to improve its sustainability profile. Due to high demand rate of packaging films in the company, a special warehouse has been allocated for keeping different kinds of packaging films. Based on the production plan of the company, procurement of these kinds of films is performed six times in a year (bi-monthly). Based on the requirements of the company, the cumulative thickness of these products has to be 180 μm. It is worth mentioning that the thickness of LLDPE and PA should be between 60 and 80 μm and 100–120 μm based on the requirements, respectively. The main suppliers of these products are PMA, MAZP, IRZA and ROLP.

4.1 *Criteria definition and selection*

In this step, in order to evaluate the suppliers based on sustainability criteria, related criteria and subcriteria were extracted from the literature and standards (Handfield et al. 2002; Chen 2005; Lu, Wu, and Kuo 2007; Kannan et al. 2008; Hutchins and Sutherland 2008; Hsu and Hu 2009; Lee et al. 2009; Awasthi, Chauhan, and Goyal 2010; Bai and Sarkis 2010a; Dai and Blackhurst 2011; GRI 2011; Amindoust et al. 2012; Büyüközkan and Çifçi 2012; Fu, Zhu, and Sarkis 2012; Shaw et al. 2012; Govindan, Khodaverdi, and Jafarian 2013; Nikolaou, Evangelinos, and Allan 2013). Afterward, these criteria and subcriteria were validated and selected by the decision-makers of the company. Managing director's representative, finance manager, logistic manager, quality assurance manager and warehouse manager are the decision-makers of the company who were asked to perform the criteria selection process. In this research, the economic subcriteria were selected based on the existed subcriteria and influencing factors in the company's current supplier evaluation system including quality, loyalty, technical capability, delivery and costs (product cost, ordering cost, transportation cost) and some modifications based on the company's experts' suggestions. For environmental and social criteria, since evaluation criteria and subcriteria can vary from a company to another company in the real world, an adjustment mechanism was carried out for selecting most relevant environmental and social criteria to the company. In order to conduct the adjustment mechanism, the list of most used social and environmental criteria and subcriteria and influencing factors in the literature was provided (Appendix 1) and shown to the experts and they were asked to select the most related ones to their company with Yes/No operators. The data of the first round of the adjustment mechanism were gathered and analysed. It is worth mentioning that the experts were asked to propose the subcriteria or influencing factors which did not exist in the list but which they could be relevant to their company. For example, managing director's representative suggested dividing staff training into average hours of training per year per personnel and per manager. Moreover, in the first round, some words were modified and some sections were modified in order to meet the company's expert's requirements. For example, greenhouse emission has become a separate subcriterion with its own influencing factors and has been separated from the pollution control subcriterion based on the company's experts' opinions during the meetings. A score of 1 was defined for each answer of Yes and 0 for each answer of NO. Afterward, the mean score of each influencing factor was calculated. A threshold of 51% was set to select the most related influencing factors. The results of the first round of adjustment process were given to the experts as reference and the results were discussed in several meetings. Subsequently, the second round of adjustment mechanism process was conducted to finalise the criteria, subcriteria and influencing factors that are relevant to the company for sustainable supplier evaluation. The results of adjustment mechanism are shown in Table 2. The list of selected criteria, subcriteria and their related influencing factors for this case study is shown in Table 2.

5. Results and discussion

5.1 *Supplier assessment regarding social and environmental criteria*

In order to weight the social and environmental issues, FAHP was utilised. The Company's experts were asked to make pairwise comparison based on Chang's FAHP (Chang 1996) using the fuzzy scale shown in Table 3 separately for social and environmental subcriteria .The results for final weight of social and environmental subcriteria are shown in Table 4.

Table 2. Selected criteria, subcriteria, and influencing factors.

Criteria	Subcriteria	Influencing factors
Economic	Cost	Purchasing cost
		Holding cost
		Ordering cost
	Quality	Product quality level
	Delivery	On time delivery reliability level
	Loyalty	Loyalty level to company
	Technical capability	Production facilities and capacities, ability to adopt with company's demand changes
Environmental	Environmental management system	Level of EMS implementation
		Environmental protection level
	Pollution	Chemical waste (raw material extraction)
		Product waste
	Green house emission	Methane emission to air
		CO_2 emission
		NO2 emission to air
Social	Occupational health and safety management system	Level of implementation for occupational health and safety system
		Percentage of workforce represented in formal joint management work health and safety committee
	Worker safety and labour health	Percent of injury per year
		Mercury (Hg)
		Sulphur dioxide (SO_2)
		Particles (PM10)
	Training education and Community development	Average hours of training per year per employee (Managers)
		Average hours of training per year per employee (Personnel)
		Number of created job opportunity

Table 3. Fuzzy numbers and linguistic variables.

Fuzzy number	Linguistic variable
(1,1,1)	Just equal
(2/3,1,3/2)	Equally important
(1,3/2,2)	More important
(3/2,2,5/2)	Strongly more important
(2,5/2,3)	Very strongly more important
(5/2,3,7/2)	Absolutely more important

Table 4. Subcriteria weights.

Criteria	Weight	Criteria	Weight
Environmental		*Social*	
EMS	0.388	OHSAS	0.4488
Pollution	0.3356	Safety	0.2756
Green house	0.2756	Training	0.2756

5.1.1 *Data collection*

In this part, all of the data regarding the selected criteria, subcriteria and influencing factors which are shown in Table 2 are gathered. A detailed explanation of data gathering process is presented as follows.

5.1.1.1 *Environmental criteria.*

5.1.1.1.1 *Green house emission*. In this step, in order to gather relative data for green house emission subcriterion, NO_2, CO_2 and CH_4 emissions were identified as the influencing factors. In this study, suppliers were asked to disclose their products mixtures which show the thickness of LLPDE and PA used in the final product. The specification of product such as thickness and weight of each material for different suppliers are shown in Table 5. For the amount of NO_2, CO_2 and CH_4 emission to air for producing 1 kg of LLPDE and PA 6 which are related to raw material extraction, data were gathered from Plastics Europe Data-set version 3.0. (Plastic Europe 1996; Plastic Europe 2000). In order to have logical data, 100 gr of the packaging film was considered as a standard scale for further calculation. Therefore, based on the different weights of materials in different mixtures which are shown in Table 5, the total amount of NO_2, CO_2 and CH_4 emissions were calculated for 100 gr of packaging film. The results are shown in Table 6. The weights of the materials (LLPDE and PA 6) in 100 gr of each mixture are calculated based on their thickness in the mixture and their related density. It is worth mentioning due to the small portion of glue in the packaging film combination (maximum 3μm), its effects were not considered in this paper.

5.1.1.1.2 *Pollution*. As shown in Table 2, chemical waste (ChW) and product waste (PW) were identified as influencing factors for evaluating suppliers in terms of pollution subcriterion. In Table 7, the amounts of these factors are shown. For product waste calculation, the product waste of each supplier was divided to their production rate in a typical month. For the amount of chemical waste for producing 1 kg of LLPDE and PA 6 regarding raw material extraction, data were gathered from Plastics Europe Data-set version 3.0. (Plastic Europe 1996; Plastic Europe 2000). Subsequently, the total amount of chemical waste for producing 100 gr of the product was calculated.

Table 5. Suppliers' products mixture.

	Thickness (μm)		Weight (gr/100 gr product)	
Supplier	PA	LLDPE	PA	LLDPE
PMA	70	110	0.4356	0.5644
MAZP	65	115	0.4067	0.5933
IRZA	72	108	0.4470	0.5530
ROPL	65	115	0.4067	0.5933

Table 6. Greenhouse emission.

Influencing factor	Unit	Supplier			
		PMA	MAZP	IRZA	ROPL
CO_2	gr/100 gr product	0.321849	0.310370066	0.326406	0.31037
NO_2	gr/100 gr product	0.000977	0.000931389	0.000995	0.000931
CH_4	gr/100 gr product	0.002834	0.002739369	0.002872	0.002739

Table 7. Pollution.

Influencing factor	Unit	Supplier			
		PMA	MAZP	IRZA	ROPL
ChW	gr/100 gr product	0.001515	0.001448	0.001542	0.001447823
PW	kg/100 kg	0.03	0.07	0.04	0.08

5.1.1.1.3 *Environmental management system*. In terms of environmental management system subcriterion, level of EMS implementation (LOEMS) and environmental protection level (EPL) were considered as influencing factors. Table 8 shows the ranking orders for evaluation of the suppliers based on these two influencing factors. As shown in Table 8, three levels of implementation have been defined for this influencing factor which are not implemented, implemented without certificate and implemented with certificate. Suppliers without any documentation for implementation of EMS (e.g. ISO 14000) are categorised into level 1. Suppliers that have done documentation for implementation of EMS and implemented EMS but have not succeeded to achieve the relevant certificates are categorised into level 2. Suppliers that have implemented EMS and achieved its relevant certificate are categorised into level 3. The score of the suppliers regarding these subcriteria are shown in Table 9.

5.1.1.2 *Social criteria.*

5.1.1.2.1 *Occupational health and safety management system (OHSMS)*. For this subcriterion, two influencing factors are defined as: level of implementation for OHSMS (LOHSMS) and percentage of workforce represented in formal

Table 8. Ranking orders.

Influencing factor	Score
LOEMS	
Not implemented	1
Implemented without certificate	2
Implemented with certificate	3
EPL	
Weak	1
Moderate	2
Good	3

Table 9. EMS.

Influencing factor	Supplier			
	PMA	MAZP	IRZA	ROPL
LOEMS	3	2	3	2
EPL	2	2	2	1

joint management work health and safety committee (PWMS). For the first influencing factor, suppliers were assessed based on the level of OHSMS in their company. The decision-makers of the company defined three levels of implementation for the system to assess the suppliers. Table 10 provides a ranking order of level of implementation. Table 10 shows that three levels of implementation have been defined for this influencing factor: (1) not implemented (2) implemented without certificate (3) implemented with certificate. Suppliers with the valid certificate of implementation of OHSMS (e.g. OHSAS 18000) are categorised into level 3. Suppliers that have done documentation for implementation of OHSMS and implemented OHSMS but have not succeeded to achieve the relevant certificates are categorised into level 2. Suppliers without any documentation for implementation of OHSMS are categorised into level 1. Likewise, for the second influencing factor, the number of workforces represented in formal joint management work health and safety committee was divided by the total workforces. The final results for this subcriterion are shown in Table 11.

5.1.1.2.2 *Work safety and labour health*. In order to assess the suppliers based on work safety and labour health subcriterion, Sulphur dioxide (SO_2), Mercury (Hg) and PM_{10} related to the raw material extraction phase and the percentage of injury per year (PI) in each supplier company have been selected. The procedures for calculating the amount of Hg, SO_2 and PM_{10} are same as greenhouse emission section. In addition, percentage of injury in a year in each supplier's company has been taken into account as an influencing factor for Work safety and labour health subcriterion. The results are shown in Table 12.

5.1.1.2.3 *Training, education and community development*. Training, education and community development includes three influencing factors which are: average hours of training per year per manager (ATM), average hours of training per year per personnel (ATP) and number of created job opportunity (NJO). These influencing factors show the responsibility of a company regarding social and employee's improvement. The data for these influencing factors regarding each supplier are shown in Table 13.

Table 10. Ranking orders.

Influencing factor	Ranking
LOHSMS	
Not implemented	1
Implemented without certificate	2
Implemented with certificate	3

Table 11. OHSAS.

Influencing factor	Supplier			
	PMA	MAZP	IRZA	ROPL
LOHSMS	3	2	3	2
PWMS	0.229885	0.1	0.125	0.12

Table 12. Work safety and labour health.

Influencing factor	Unit	Supplier			
		PMA	MAZP	IRZA	ROPL
PI	Injury/100 staff	0.04	0.06	0.05	0.07
Hg	gr/100 gr product	2.05E-10	2.01E-10	2.06E-10	2.01E-10
SO2	gr/100 gr product	9.22E-04	8.84E-04	9.37E-04	8.84E-04
PM10	gr/100 gr product	1.92E-04	1.87E-04	1.94E-04	1.87E-04

Table 13. Training, education, and Community development.

Influencing factor	Supplier			
	PMA	MAZP	IRZA	ROPL
ATM	63	35	68	21
ATP	41	18	35	15
NJP	174	80	160	50

5.1.2 *Determining supplier social and environmental evaluation using fuzzy approach*

In this step, in order to evaluate the suppliers-based social and environmental criteria, a fuzzy rule-based approach is utilised. Based on reviewing the literature and consulting with the experts of the company, the decision was made to define low, medium and high as membership grades of input variables. Also, very low, low, medium, high and very high were defined as membership grades of output variables. The fuzzified inputs are shown in Table 14. Afterward, rules were defined based on the experts' opinions. Table 15 shows some rules from the rule base. Then, a rule-based fuzzy system was used to process the data. MATLAB fuzzy inference system was utilised in step to perform the fuzzy evaluation.

Table 14. Fuzzified input variables.

Linguistic variable	Fuzzy number	Linguistic variable	Fuzzy number	Linguistic variable	Fuzzy number	Linguistic variable	Fuzzy number
Input: CH_4		Input: NO_2		Input: CO_2		Input: SO_2	
Low	[0.00235 0.0026 0.00285]	Low	[0.0008 0.0009 0.001]	Low	[0.3 0.31 0.32]	Low	[0.0007 0.0008 0.0009]
Medium	[0.0026 0.00285 0.0031]	Medium	[0.0009 0.001 0.0011]	Medium	[0.31 0.32 0.33]	Medium	[0.0008 0.0009 0.001]
High	[0.00285 0.0031 0.00335]	High	[0.001 0.0011 0.0012]	High	[0.32 0.33 0.34]	High	[0.0009 0.001 0.0011]
Input: Hg		Input: PM_{10}		Input: PI		Input: PWMS	
Low	[1.95e-010 2e-010 2.05e-010]	Low	[0.00017 0.00018 0.00019]	Low	[-.04 0 .04]	Low	[0 0.1 0.2]
Medium	[2e-010 2.05e-010 2.1e-010]	Medium	[0.00018 0.00019 0.00020]	Medium	[0 .04 .08]	Medium	[0.1 0.2 0.3]
High	[2.05e-010 2.1e-010 2.15e-010]	High	[0.00019 0.00020 0.00021]	High	[.04 .08 .12]	High	[0.2 0.3 0.4]
Input: LOHSAS		Input : ATP		Input: ATM		Input: NJO	
Low	[0 1 2]	Low	[0 0 40]	Low	[-60 0 60]	Low	[0 0 100]
Medium	[1 2 3]	Medium	[0 40 80]	Medium	[0 60 120]	Medium	[0 100 200]
High	[2 3 4]	High	[40 80 120]	High	[60 120 180]	High	[100 200 200]
Input: PW		Input: ChW		Input: EPL		Input: LOEMS	
Low	[0 0 0.05]	Low	[0.0011 0.0013 0.0015]	Low	[0 1 2]	Low	[0 1 2]
Medium	[0 0.05 0.1]	Medium	[0.0013 0.0015 0.0017]	Medium	[1 2 3]	Medium	[1 2 3]
High	[0.05 0.1 0.15]	High	[0.0015 0.0017 0.0019]	High	[2 3 4]	High	[2 3 4]

Table 15. Sample rules.

1	If (CO_2 is low) and (CH_4 is low) and (NO_2 is low) then (output1 is very high)
2	If (CO_2 is high) and (CH_4 is high) and (NO_2 is high) then (output1 is very low)
3	If (ChW is low) and (PW is low) then (output1 is very high)
4	If (ChW is high) and (PW is high) then (output1 is very low)
5	If (ChW is high) and (PW is low) and then (output1 is medium)

Table 16. Suppliers scores in environmental and social criteria.

	Subcriteria	Subcriteria weights	PMA	MAZP	IRZA	ROPL
Environmental	EMS	0.388	0.75	0.5	0.75	0.25
	Pollution	0.3356	0.578	0.473	0.498	0.439
	Green house	0.2756	0.527	0.763	0.367	0.756
	Overall score		0.630218	0.563022	0.559274	0.452682
Social	OHSAS	0.4488	0.76	0.25	0.572	0.31
	Safety	0.2756	0.435	0.559	0.395	0.522
	Training	0.2756	0.676	0.341	0.602	0.327
	Overall score		0.64728	0.36024	0.531487	0.373112

Based on Equation (1), overall scores of suppliers in environmental and social criteria were calculated. The results are shown in Table 16. The overall scores of suppliers in social and environmental criteria were used as parameters of multi-objective mathematical model. From the results it can be perceived that PMA is the best in terms of environmental and social issues, respectively. In order to make a continuous improvement, the weak points of each supplier are identified and reported to them. The suppliers can improve their weak points to have a more sustainable profile.

5.2 *Suppliers evaluation based on economic qualitative criteria*

In this step, as shown in Table 2, quality, delivery, technical capability and loyalty were selected as the main subcriteria of economic qualitative criterion. These subcritera were selected based on the existing criteria in the supplier evaluation system of the company. Since the suppliers are assessed based on this criteria in a qualitative manner in the company, this category of criteria were named economic qualitative criteria. For quality subcriterion, the qualities of the products provided by the suppliers in terms of physical properties (e.g. transparency, sealability and strength) are evaluated in the company. The level of on-time delivery reliability of supplier is defined as the influencing factor of delivery subcriterion. Suppliers are evaluated based on the historical data in the company regarding the level of on-time delivery reliability. The experts of the company evaluate the supplier qualitatively based on this influencing factor. For loyalty subcriterion, the level of supplier loyalty and commitment to the company is evaluated based on the experts' opinions. Regarding the technical capability subcriterion, capabilities of suppliers in terms of production facilities and their ability

Table 17. Economic subcriteria definitions.

Subcriteria	Definition	Reference
Quality	Quality of the products provided by a supplier	Lee et al. (2009), Dai and Blackhurst (2011), Büyüközkan and Çifçi (2012), Zhang et al. (2013)
Delivery	The ability to follow the predefined delivery Schedule and their on time delivery reliability	Shaik and Abdul-Kader (2011), Govindan, Khodaverdi, and Jafarian (2013)
Technical capability	The level of capabilities of suppliers in terms of production facilities and their ability to adopt themselves with company's demand changes	Shaik and Abdul-Kader (2011), Govindan, Khodaverdi, and Jafarian (2013)
Loyalty	The level of supplier management loyalty and commitment to the company	Choy, Lee, and Lo (2004), Sevkli et al. (2007)

Table 18. Suppliers' scores in economic qualitative criterion.

		Subcriteria				
		Quality	Delivery	Loyalty	Technical	Final weight
Weight		0.337386	0.277836	0.218294	0.166484	
Supplier	PMA	0.302391	0.382008	0.334701	0.296203	0.330534629
	MAZP	0.197609	0.109438	0.221766	0.132036	0.167468169
	IRZA	0.302391	0.254277	0.221766	0.439725	0.294287384
	ROPL	0.197609	0.254277	0.221766	0.132036	0.207709818

to adopt themselves with company's demand changes are evaluated. Table 17 provides the economic criteria and their definition.

Company's experts were requested to do pairwise comparison using the fuzzy scale provided in Table 3. Then, the score of each supplier was calculated using Chang's FAHP. The final results of this step are shown in Table 18. The weight of each supplier in this step shows its performance. It means supplier with more weight is the better. So, it can be perceived that PMA and MAZP have the best and worst performance regarding economic qualitative criterion, respectively.

5.3 *Order allocation and model optimisation*

In this research, due to the multi-objective nature of the proposed model, a weighted sum method and an augmented ε-constraint method are used for optimisation purposes. The steps of these solution methods are briefly given in the following sections

5.3.1 *Weighted sum method*

A multi-objective model can be shown as follows:

$$\underset{x \in X}{\text{Max}} (f_1(x), \ldots, f_n(x)) \tag{23}$$

where X is the feasible region. This model can be solved by solving single-objective problem as follows:

$$\underset{x \in X}{\text{Max}} \sum_{i=1}^{n} \mathrm{w}_i . f_i \tag{24}$$

Initially, each objective function is optimised separately and the negative ideal solution (worst solution) and positive ideal solution (best solution) of them are found. Since the values of objective functions (fi) vary in different scales, Equation (25) is used to normalise the objective functions.

$$f_i^{/} = \begin{cases} \frac{NIS_{fi} - fi}{NIS_{fi} - PIS_{fi}} & \text{for minimization objective function} \\ \frac{f_i - NIS_{fi}}{PIS_{f_i} - NIS_{fi}} & \text{for maximization objective function} \end{cases} \tag{25}$$

where, $f_i^{/}$ is the normalised value of the ith objective function, NIS_{fi} is the negative ideal solution of ith objective function and PIS_{fi} is the best solution or the positive ideal solution of ith objective function. Then, a weight w_i is assigned to each normalised objective which is determined by FAHP. Next, the model is changed to a single-objective function (f) by summing up all weighted objective functions as shown in Equation (26).

$$\text{Max}(f) = \sum_{i=1}^{n} \mathrm{w}_i f_i' \tag{26}$$

Tables 19–21 provide the related data for the optimisation process. The data are provided for four suppliers, six periods and three products. FAHP was used in order to determine the weight of each objective function. The experts of the company provided pairwise comparisons of the relative importance of objective functions based on the fuzzy scale shown in Table 3. According to the steps of FAHP, the final weight of each objective function was calculated as shown in Table 22.

Table 19. Demands.

	Product	Period 1	2	3	4	5	6
D_{it}	Film 322	64,000	64,000	64,000	72,000	72,000	72,000
	Film 420	80,000	80,000	80,000	88,000	88,000	88,000
	Film 422	80,000	80,000	80,000	88,000	88,000	88,000

Table 20. Holding cost and needed space for each kg of product.

Product	H_i (IRR/kg)	V_i (m^3/kg)
Film 322	1666.667	0.001288
Film 420	1625	0.00168
Film 422	1625	0.001688

Table 21. Supplier/product data.

	Product	Supplier PMA	MAZP	IRZA	ROPL
P_{ij} (IRR)	Film 323	81,000	80,000	82,000	79,000
	Film 420	78,000	77,000	79,000	77,000
	Film 422	78,000	77,000	79,000	77,000
C_{ij} (kg/t)	Film 323	30,000	30,000	35,000	20,000
	Film 420	45,000	40,000	50,000	25,000
	Film 422	45,000	40,000	50,000	25,000
O_j (IRR)		7,000,000	10,000,000	7,500,000	8,000,000
φ_j (IRR/kg)		172.2	486.6	126	30
E_{ij}		0.630218	0.563022	0.559274	0.452682
τ_{ij}		0.64728	0.36024	0.531487	0.373112
ω_{ij}		0.3305	0.1674	0.2942	0.2077

Table 22. Weight of objective functions.

Objective function	Cost	Economic qualitative	Environment	Social
Weight	0.277836	0.2182940	0.337386	0.166484

The linear programming software LINGO 9 was used to perform the optimisation process by means of a computer featured by 8 Gigabytes RAM with an Intel Core i5 CPU. The final results of optimisation for the problem of sustainable supplier selection integrated with multi-period multi-product lot-sizing are shown in Table 23. The results show the quantities of products allocated to each supplier in each period, while the sustainability objective functions are satisfied simultaneously.

5.3.2 *Augmented ε-constraint method*

In this research, an augmented ε-constraint method was also used for optimisation purposes. The augmented ε-constraint method produces only Pareto efficient optimal solutions and avoids inefficient ones (Aghaei, Amjady, and Shayanfar 2011; Du et al. 2014). In the ε-constraint method, one of the objective functions is designated as the main objective function to be optimised while the other objective functions appear as the model constraints. Considering the multi-objective model presented in Equation (23), the augmented ε-constraint model can be shown as follows (Mavrotas 2009):

$$\underset{x\in X}{\mathrm{Max}}\left(f_1(x)+\partial*\left(\frac{s_2}{r_2}+\frac{s_3}{r_3}+\cdots+\frac{s_i}{r_i}\cdots+\frac{s_n}{r_n}\right)\right) \tag{27}$$

Subject to

$$f_2(x)-s_2=\varepsilon_2 \tag{28}$$

$$f_3(x)-s_3=\varepsilon_3 \tag{29}$$

$$\cdots\cdots$$

$$i\in[2,n] \tag{31}$$

$$s_i\in R^{+} \tag{32}$$

Optimal solutions of the model are achieved through parametric variation of the right hand side (ε_2, $\varepsilon_3\ldots,\varepsilon_n$) of the newly added constraints. The Pareto-optimal solutions are obtained, where r_i is the range of the ith objective function, ∂ is a small number between 0.001 and 0.000001, and s_i is a non-negative slack variable. Initially, the values of NIS_{fi} and PIS_{fi} for each objective function are calculated. Then, the range of the ith objective function is calculated by:

$$r_i=PIS_{fi}-FIS_{fi} \tag{33}$$

Afterwards, r_i is divided into l_i equal intervals. Subsequently, l_i+1 grid points are achieved through Equation (34) which are set as the values of ε_i.

Table 23. Order allocation.

x_{ijt}	Quantity	x_{ijt}	Quantity	x_{ijt}	Quantity	x_{ijt}	Quantity	x_{ijt}	Quantity
x_{111}	30,000	x_{142}		x_{233}	35,000	x_{324}		x_{116}	30,000
x_{121}		x_{212}	45,000	x_{243}		x_{334}	43,000	x_{126}	7000
x_{131}	34,000	x_{222}		x_{313}	45,000	x_{344}		x_{136}	35,000
x_{141}		x_{232}	35,000			x_{115}	30,000	x_{146}	
				x_{323}					
x_{211}	45,000	x_{242}		x_{333}	35,000	x_{125}	7000	x_{216}	45,000
x_{221}		x_{312}	45,000	x_{343}		x_{135}	35,000	x_{226}	
x_{231}	35,000	x_{322}		x_{114}	30,000	x_{145}		x_{236}	43,000
x_{241}		x_{332}	35,000	x_{124}	7000	x_{215}	45,000	x_{246}	
x_{311}	45,000	x_{342}		x_{134}	35,000	x_{225}		x_{316}	45,000
x_{321}		x_{113}	30,000	x_{144}		x_{235}	43,000	x_{326}	
x_{331}	35,000	x_{123}		x_{214}	45,000	x_{245}		x_{336}	43,000
x_{341}		x_{133}	34,000	x_{224}		x_{315}	45,000	x_{346}	
x_{112}	30,000	x_{143}		x_{234}	43,000	x_{325}			
x_{122}		x_{213}	45,000	x_{244}		x_{335}	43,000		
x_{132}	34,000	x_{223}		x_{314}	45,000	x_{345}			

$$\varepsilon_i^{\eta} = NIS_{fi} + \frac{r_i}{l_i} \times \eta \tag{34}$$

where η is the number of grid points. The augmented ε-constraint model should be solved for each vector of ε. Therefore, $\prod_{i=2}^{n}(l_i + 1)$ optimisation sub-problems should be solved.

LINGO 9 was used again to solve the problem. Twenty-seven grid points were generated and the model was solved based on them. Among 27 optimisation sub-problems, 13 sub-problems had become infeasible. Therefore, these sub-problems were discarded. Table 24 shows the values of objective functions for 14 feasible sub-problems.

In order to facilitate the experts' decision-making process for selecting the most preferred Pareto-optimal solutions among all of the solutions, a fuzzy approach was used as follows (Aghaei, Amjady, and Shayanfar 2011; Du et al. 2014):

$$\alpha_i^l = \begin{cases} 1 & f_i^l \leq f_i^{\min} \\ \frac{f_i^{\max} - f_i^l}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \leq f_i^l \leq f_i^{\max} \quad \text{for minimization} \\ 0 & f_i^l \geq f_i^{\max} \end{cases} \tag{35}$$

$$\alpha_i^l = \begin{cases} 0 & f_i^l \leq f_i^{\min} \\ \frac{f_i^{\max} - f_i^l}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \leq f_i^l \leq f_i^{\max} \quad \text{for maximazation} \\ 1 & f_i^l \geq f_i^{\max} \end{cases} \tag{36}$$

where f_i^l shows the value of ith objective function in lth Parto-optimal solution. α_i^lrepresents the value of membership function of f_i^l. The total value of membership function for lth Pareto-optimal solution which was defined as the total value of sustainable purchasing (*TVSP*) is calculated by:

$$TVSP^l = \sum_{i=1}^{n} \mathrm{w}_i \alpha_i^l \tag{37}$$

As shown in Table 24, some of the Pareto-optimal solutions have similar values of objective functions. Hence, within the similar solutions, we have only used one of them for the selection process. Table 25 shows the *TVSP* for each Pareto-optimal solution. The solution with the highest *TVSP* is selected as the most preferred one.

Based on the results shown in Table 25, the Pareto-optimal solution achieved through solving sub-problem 3 was selected as the most preferred solution. After sub-problem 3, sub-problem 5 and sub-problem 7 were ranked in second and third place, respectively.

Table 24. Pareto solution obtained using augmented ε-constraint method.

Sub-problem no.	Cost	Economic qualitative	Environmental	Social
Sub-problem 1	0.1108080E + 12	286718.4	741517.9	562601.6
Sub-problem 2	0.1111323E + 12	363854.8	773303.9	698381.8
Sub-problem 3	0.1126257E + 12	440990.8	840773.2	832630.7
Sub-problem 4	0.1111421E + 12	322643.4	793445.4	642793.0
Sub-problem 5	0.1116939E + 12	362912.8	845372.9	728070.9
Sub-problem 6	0.1111305E + 12	363419.9	773124.7	697616.3
Sub-problem 7	0.1112316E + 12	363854.6	793445.3	707579.9
Sub-problem 8	0.1112316E + 12	363854.6	793445.3	707579.9
Sub-problem 9	0.1126257E + 12	440990.8	840773.2	832630.7
Sub-problem 10	0.1126257E + 12	440990.8	840773.2	832630.7
Sub-problem 11	0.1126257E + 12	440990.8	840773.2	832630.7
Sub-problem 12	0.1111323E + 12	363854.8	773303.9	698381.8
Sub-problem 13	0.1112179E + 12	357516.5	793446.0	697616.2
Sub-problem 14	0.1116939E + 12	362912.8	845372.9	728070.9

5.4 *Comparisons*

For comparison purposes, the solution quality of weighted sum approach was compared with augmented ε-constraint method. In order to perform the comparison, we used Equation (37) to achieve the *TVSP* of each optimisation approach. The results are shown in Table 26.

As shown in Table 26, the augmented ε-constraint method leads to a higher *TVSP* rather the weighted sum approach. Therefore, based on discussion with the company's experts, the result achieved through augmented ε-constraint method was selected to be used in the company. It is worth mentioning that the *TVSP* is calculated based on a specific group of data and this value is changed by the minimum and maximum of each group of data.

Likewise, a comparison was performed between our proposed multi-objective model and a cost-based single-objective model developed by Basnet and Leung (2005) which considered only the first objective function of our proposed model. The *TVSP* was used again as a measure to compare the results achieved by the different model. The values of objective functions and *TVSP* for our proposed multi-objective model and cost-based single-objective model are shown in Table 27. The results show that if the sustainability objective functions were not considered in the proposed model, the *TVSP* would be reduced. It means the orders in each period were allocated to the suppliers with less sustainability profiles using the cost-based single-objective lot-sizing model.

6. Managerial implications

The proposed model helps companies to select the appropriate suppliers for each product in each period while optimising the lot size of each product based on sustainability criteria. The results of the rule-based weighted fuzzy approach

Table 25. *TVSP* for each Pareto optimal solution.

Sub-problem	Cost	Economic qualitative	Environmental	Social	*TVSP*
Sub-problem 1	1.1080800E + 11	286718.4	741517.9	562601.6	2.78E-01
Sub-problem 2	1.1113230E + 11	363854.8	773303.9	698381.8	5.24E-01
Sub-problem 3	1.1262570E + 11	440990.8	840773.2	832630.7	7.07E-01
Sub-problem 4	1.1114210E + 11	322643.4	793445.4	642,793	4.96E-01
Sub-problem 5	1.1169390E + 11	362912.8	845372.9	728070.9	6.90E-01
Sub-problem 6	1.1113050E + 11	363419.9	773124.7	697616.3	5.23E-01
Sub-problem 7	1.1123160E + 11	363854.6	793445.3	707579.9	5.80E-01
Sub-problem 13	1.1121790E + 11	357516.5	793,446	697616.2	5.67E-01

Table 26. Comparison of augmented ε-constraint method and weighted sum approach.

Model	Objective functions values				*TVSP*
	Cost	Economic qualitative	Environment	Social	
Augmented ε-constraint method	1.1262570E + 11	440990.8	840773.2	832630.7	0.662614
Weighted sum approach	1.126623E + 11	440145.7	843090.4	832360.4	0.337386

Table 27. Comparison of single and multi-objective model.

Model	Objective functions values				*TVSP*
	Cost	Economic qualitative	Environment	Social	
Multi-objective	1.1262570E + 11	440990.8	840773.2	832630.7	0.72
Single objective	1.108080E + 11	286718.3	741517.7	562601.3	0.28

for supplier evaluation can help companies to recognise the opportunities for the improvement of the suppliers' sustainability profile. Furthermore, the proposed approach can be applied as a road map for suppliers to constantly assess and evaluate themselves rather than be assessed by other large organisations which are seeking for more sustainable suppliers.

In addition, this evaluation helps companies to identify the most sustainable mixture design of the products being purchased from the suppliers. Based on the discussion with the company's experts, it was decided to conduct a research for determining the optimised mixture of material for the packaging in terms of sustainability. For example, production of packaging films with different portions of PA and LLDPE lead to different amounts of greenhouse emission and pollution. This issue highly attracted the attention of the experts of the company.

After solving the multi-objective using the augmented ε-constraint method, the results were shown to the company's experts to select their most preferred one. It was hard for the decision-makers to select the best solution among all of the Pareto-optimal solutions. Therefore, based on discussion with the experts and their suggestion, a systematic approach was used to calculate the *TVSP* of each Pareto-optimal solution. Considering the *TVSP* of Pareto-optimal solutions and based on the discussion with the company's experts, the result achieved through solving sub-problem 3 was selected as the most preferred one. During the discussion with the experts, the finance manager of the company suggested to select the Pareto-optimal solution of sub-problem 5 due to its lower cost compared to the result of solving sub-problem 3 and their small difference in terms of *TVSP*. Hence, it was discussed again during the meeting to make a final decision. However, the other experts had stayed with their decisions and the Pareto-optimal solution of sub-problem 3 was selected to be considered in the procurement plan of the company. It was mentioned by the experts that the costs can be reduced by negotiation with the suppliers that are going to be allocated based on the procurement plan of solving sub-problem 3.

The results of multi-objective model optimisation show that how considering sustainability issues on the integrated problem of multi-period multi-product lot-sizing can lead to a better value of sustainable purchasing. Although the results of the multi-objective model lead to a higher cost to the company compared to the results of single-objective model, the company's managers agreed to make their procurement based on the results of the multi-objective model because they believed it can improve their sustainability profile and consequently can make competitive advantages and long-term profit. In comparison with the current supplier evaluation system, our proposed model provides an order allocation system for the companies which were not available there. They only considered product cost and economic criteria for supplier evaluation and ranking purposes. During a meeting with the company's experts, they mentioned that the proposed method which considers all types of costs and sustainability criteria would help them to choose an efficient procurement plan in a sustainable environment.

7. Conclusion remarks

In this paper, we have developed a comprehensive framework and a multi-objective mathematical model for the problem of sustainable supplier selection integrated with multi-period multi-product lot-sizing. First of all, the related sustainable criteria, subcriteria and influencing factors are determined based on literature and experts' opinions. Then, FAHP is used to weight the selected criteria and subcriteria. This step is followed by a rule-based weighted fuzzy approach to evaluate the suppliers based on social and environmental criteria. Capability to deal with severe uncertainty and ability to evaluate qualitative and quantitative data simultaneously are the most important advantages of the proposed weighted fuzzy approach. Subsequently, FAHP is used again for evaluating the suppliers based on the economic qualitative criteria. These scores are used as parameters for developing the multi-objective mathematical model which is developed in this research. The applicability and proficiency of the proposed model is elucidated with a case study of packaging films in a food industry.

In order to highlight the importance of sustainability objective functions considered in this research, the proposed model is compared with a cost-based single-objective model of multi-period multi-product lot-sizing with supplier selection. The comparisons in this research show the influence of social, environmental and economic qualitative criteria on the integrated problem of supplier selection and multi-period multi-product lot-sizing. The results of the comparisons show that our proposed approach leads to a higher *TVSP* rather than the single-objective cost-based model.

One of the main limitations for measuring the performance of suppliers is about obtaining validated data on suppliers' social and environmental performances. Hence, focusing on some strategies such as vertical integration and collaborative relationship with suppliers can help companies to obtain validated data on suppliers' performances for effectively monitoring and evaluating them based on identified influencing factors.

For the future works, there might be some potential avenues of research for sustainable supplier selection and order allocation in a closed loop supply chain. Moreover, further research might explore the problem of sustainable supplier selection and order allocation in which the uncertainty and dynamic nature of some parameters are taken into account.

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Appendix 1. Adjustment mechanism

Criteria	Subcriteria	Influencing factor	Relevant? (Yes/No)
Environmental	Environmental management system	Environmental management certificate	
		Internal control process	
		Environmental policies	
		Environmental protection level	
	Pollution control	Green house emission	
		Chemical waste	
		Waste water	
		Product waste	
	Green competencies	Use of environmental friendly materials	
		Green packaging	
		Recycling capability	
		Energy consumption control	
		Eco-design for reuse and recycling	
Social	Occupational health and safety management system	Level of OHSAS 18001	
		Personnel engagement in Health and safety committee	
		Health and safety policies	
	Worker safety and labor health	Health and safety incidents	
		Hazardous materials for workers health	
		Worker safety practice	
	Training education and community influence	Employee's training	
		The interests and rights of employee	
		Employee contracts	
		Number of job opportunity	
		Grants and donations	
	Contractual stakeholders influence	Information disclosure	
		Procurement standard	
		Stakeholder engagement	