Green supplier selection and order allocation: a nonlinear stochastic model

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Amir Hossein Azadnia
National University of Ireland, Maynooth

Masoud Rahiminezhad Galankashi
Imam Khomeini International University

Syed Ahmad Helmi
Universiti Teknologi Malaysia

Farimah mokhatab rafiei
Tarbiat Modares University

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Pooria Hashemzahi

Department of Materials, Manufacturing and Industrial Engineering,
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia,
Skudai, Johor, Malaysia
and
Department of Industrial Engineering,
Faculty of Engineering,
Kharazmi University,
Tehran, Iran
Email: Pourya_hashemzahi@yahoo.com

Amirhossein Azadnia

Department of Industrial Engineering,
Ayatollah Amoli Branch,
Islamic Azad University,
Amol, Iran
Email: Azadnia.ie@gmail.com

Masoud Rahiminezhad Galankashi*

Department of Materials, Manufacturing and Industrial Engineering,
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia,
Skudai, Johor, Malaysia
and
Department of Industrial Engineering,
Tarbiat Modares University,
Tehran, Iran
Email: Masoud.rahiminejad@yahoo.com
*Corresponding author

Syed Ahmad Helmi

Department of Materials, Manufacturing and Industrial Engineering,
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia,
Skudai, Johor, Malaysia
and
Center for Engineering Education,
Universiti Teknologi Malaysia,
Skudai, Johor, Malaysia
Email: Helmi@utm.my

Farimah Mokhatab Rafiei

Department of Industrial Engineering,
Tarbiat Modares University,
Tehran, Iran
Email: F.mokhatab@modares.ac.ir

Abstract: Supplier selection and order allocation is a complex managerial decision in today's competitive markets. As an important section of this area, green supplier section has been properly focused in previous literature. However, joint supplier selection and order allocation under stochastic demand is less investigated. Firstly, a fuzzy analytic hierarchy process (FAHP) is applied to weight and select suppliers in terms of economic and environmental criteria. Secondly, a multi-objective nonlinear programming (MONLP) is developed and solved by genetic algorithm (GA) for the aim of order allocation. Findings of this study assist managers to systemically deal with the real-world problem of green supplier selection with different priorities and order quantities.

Keywords: green supplier selection; fuzzy analytic hierarchy process; FAHP; genetic algorithm; GA; stochastic supplier selection; Malaysia.

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Biographical notes: Pooria Hashemzahi is a PhD candidate in the field of industrial engineering. His main areas of interests include supplier selection and green supply chain management.

Amirhossein Azadnia is an Assistant Professor of Industrial Engineering. His main areas of interests include supply chain management (SCM) and decision-making.

Masoud Rahiminezhad Galankashi received his BSc, MSc and PhD in the field of Industrial Engineering from QIAU and UTM, respectively. He is currently working on different areas of the industrial engineering focusing on SCM. His research interests include SCM, simulation, MCDM/MADM, mathematical modelling, lean manufacturing and DOE.

Syed Ahmad Helmi is an Assistant Professor of Industrial Engineering. His main area of interests includes system dynamics and SCM.

Farimah Mokhatab Rafiei is an Associate Professor of Industrial Engineering at Tarbiat Modares University (TMU) in Tehran, Iran. She received her PhD in Industrial Engineering (Iran). She holds two Masters, one in systems planning concentrating operations research (Iran) and another in business concentrating finance (USA). She also received her BSc in Industrial Engineering (USA). She has published more than 80 journal and conference papers.

1 Introduction

Supplier selection is an important task which should be considered in today's competitive markets (Galankashi et al., 2016a). Different companies, service providers and businesses have highlighted the importance of purchasing and supplier selection to improve the performance. With the advent of green manufacturing, green supplier selection has been accepted as an important enabler to address the environmental concerns (Bai and Sarkis, 2010). However, although green manufacturing has been discussed by numerous studies in previous literature, it is less investigated in conjunction with supplier selection process, especially when focusing on order allocation (Galankashi et al., 2015). In other words, green supplier selection and order allocation is less investigated in previous studies. In this regard, identifying the specific measures of assessing suppliers from green perspectives, integrating these measures in a multiple-criteria decision-making (MCDM) problem, developing appropriate models to determine the order allocation of suppliers and finally solving them is a challenge for managers, scholars and practitioners. While the majority of real world problems are happening in uncertain and stochastic environments, they are less examined in previous literature. In other words, the majority of previous studies have considered the parameters of order allocation model as a deterministic variable. In addition, as supplier selection is a MCDM problem, the comparison process of criteria and alternatives can be conducted in fuzzy environments. Therefore, the decision makers prefer to make their judgments by linguistic terms instead of deterministic and numerical scales. This ignorance of previous literature is somewhat due to the complexities linked with modelling of stochastic decisions. In addition, supplier selection process only determines the ranking of suppliers with regard to the decision criteria. However, the real world problems are more complex and need to determine the optimum purchasing quantity of each item from each supplier in each period. In this regard, order allocation models are suggested to determine the exact quantity of purchasing plan with regard to different objective functions of the companies. So, in summary, the research problems include the integration of appropriate green supplier selection criteria, MCDM and mathematical modelling to determine the best supplier and the optimum purchasing plan in fuzzy and stochastic environments. Therefore, this study develops an integrated model for green supplier selection and order allocation. The following research questions are addressed in this study:

1 How the green supplier selection can be conducted?

2 How MCDM techniques can aid the supplier selection process?

3 What is the optimum purchasing quantity of each item from each supplier in each period?

This study has been conducted in manufacturing sector of Malaysia. However, the research methodology, applied framework and the obtained results can be applicable for researchers, managers and practitioners who are interested in supplier selection and order allocation topic. This research contributes in developing the green supplier selection criteria, linking them with MCDM techniques and considering the decision makers' judgements in fuzzy environments. It develops a novel multi-objective nonlinear stochastic model for the aim of order allocation which reflects the uncertain nature of real world problems. Therefore, from research and practice viewpoints, the contributions of this research are novel as no comparable study has been done before.

2 Literature review

2.1 Market complexity

The complexity of markets provides an opportunity for firms, managers and researchers to focus on their supply chain instead of sole concentration on companies (Rahiminezhad Galankashi et al., 2019). Suppliers, as a part of the supply chain, play a functional role in this network. The supplier selection is a MCDM task as it involves numerous qualitative and quantitative data. These MCDM processes include but not limited to data envelopment analysis (DEA) (Liu et al., 2000; Forker and Mendez, 2001; Galankashi et al., 2016c; Fakhrzad and Nasrollahi, 2018), analytic hierarchy process (AHP) (Liu and Hai, 2005; Boran et al., 2009; Galankashi et al., 2016a), mathematical programming (Ghodsypour and O'Brien, 2001; Talluri and Narasimhan, 2005), analytic network process (ANP) (Bayazit, 2006; Gencer and Gürpinar, 2007; Dargi et al., 2014; Galankashi et al., 2015), genetic algorithm (GA) (Yeh and Chuang 2011), fuzzy logic (Chen et al., 2006; Florez-Lopez, 2007) and TOPSIS (Boran et al., 2009) to address the supplier selection problem. In addition to MCDM nature of today's competitive markets, there are many similar problems with sole or multiple objectives (Kumar, 2017; Panicker et al., 2018). Finally, there are numerous complex problems which should be assessed in fuzzy environments (Paras and Curteza, 2018; Fakhrzad and Bazeli, 2018; Hemmati et al., 2018; Khorramrouz and Galankashi, 2019).

2.2 Supplier selection with environmental considerations

Appropriate supplier selection improves the performance of supply chains. This improvement is attained by optimum order quantity and reduced time to decrease total purchasing cost and satisfy customer requirements (Verma and Pullman, 1998; Boran et al., 2009; Kannan et al., 2013; Azadnia et al., 2015; Galankashi et al., 2016b). Numerous studies have addressed supplier selection in the supply chain (Min and Galle, 1997, 2001; Lu et al., 2007; Hsu and Hu, 2009; Lee et al., 2009; Bai and Sarkis, 2010; Genovese et al., 2010; Yeh and Chuang, 2011; Amindoust et al., 2012; Galankashi et al., 2013).

Lately, environmental factors are considered as significant issues in business-marketing. Moreover, governments are more conscious about pollution and protecting the earth, and their legal policies are forcing firms to pay more attention to sustainability. Therefore, green supplier selection is significant in attaining a green supply chain (Shaw et al., 2012). Numerous researchers have investigated the green supplier selection problem (Handfield et al., 2002; Kannan et al., 2008; Lee et al., 2009; Chen et al., 2010; Büyüközkan and Çifçi, 2011; Yeh and Chuang, 2011; Kannan et al., 2013; Zhang et al., 2013; Azadnia et al., 2015; Galankashi et al., 2015).

2.3 Related studies

Supplier selection is the most important activity of purchasing management in the supply chain section. Dickson (1966) proposed 23 dissimilar criteria to be considered in assessing suppliers. In line with this preliminary study, recently, numerous scholars (Yeh and Chuang, 2011; Kannan et al., 2013; Zhang et al., 2013; Azadnia et al., 2015) investigated this topic and presented models for supplier selection and order allocation. Ho et al. (2010) presented a literature review on supplier selection approaches between 2000 and 2008 according to 78 published journal articles. As reported in the review, 58% of the researchers used individual approaches, with DEA, mathematical programming and AHP. In addition, integrated AHP, fuzzy set theory and multi-objective programming (MOP) are other popular approaches in supplier selection and order allocation (Weber and Ellram, 1993; Amid et al., 2006; Demirtas and Üstün, 2008; Huo and Wei, 2008; Wu et al., 2010; Jolai et al., 2011).

Formerly, the major criteria of supplier selection were cost, quality and time. Meanwhile, with the increasing apprehension about environmental protection, new factors have become a part of supplier selection. Therefore, companies encourage suppliers to improve their environmental performance by entering related factors in purchasing decisions. Identifying companies with environmental and green capabilities, identifying a measuring system to evaluate the suppliers' environmental performance and choosing the most effective method to select suppliers, are three phases in green supplier selection (Noci, 1997). The following are some related studies on green supplier selection and order allocation.

Liao and Rittscher (2007) suggested the expansion of a multi-objective supplier selection model under stochastic demand. A GA was developed to manage the combinatorial optimisation issue of this study. Zhang and Zhang (2011) conducted mix integer programming (MIP) for supplier selection and order allocation problem with fixed purchasing costs under stochastic demand. In a similar research, Awasthi et al. (2009) presented a model for supplier selection under the uncertain demand. The lack of environmental factors in supplier selection and order allocation is evident in their study. Kuo et al. (2010) developed a model intended for green supplier selection. This study integrated artificial neural network (ANN) and DEA with ANP for the aim of green supplier selection. The supplier selection criteria were cost, quality, environmental factors, lead time, service and corporate social responsibility. In another similar research, Yeh and Chuang (2011) constructed a multi-objective linear model (MOLP) with four objective functions of cost, quality, time and green appraisal score. Azadnia et al. (2015) proposed an integrated FAHP and multi-objective mathematical programming. The criteria for supplier selection and order lot-sizing problem were cost, all-out social score, environmental score and all-out economic qualitative score. Furthermore, Kannan et al. (2013) offered an integrated fuzzy multi-attribute utility model and MOP intended to rate and select the best green suppliers. In this study, cost, quality, delivery time, technology capability and environmental competency were the main criteria. Correspondingly, pollution, resource consumption, environmental management system (EMS) and eco-design were defined as sub-criteria of environmental factor. Galankashi et al. (2015) prioritised the green supplier selection criteria using FANP approach. Banaeian et al. (2018) developed a study to compare different MCMD techniques in a fuzzy environment. The considered techniques include VIKOR, GRA and TOPSIS. In another study, Haeri and Rezaei (2019) integrated economic and environmental criteria of green supplier selection using a grey-based approach. In addition, this study developed a new weight assignment approach by integrating the fuzzy grey cognitive maps and best-worst methodology. In a very recent study, Dobos and Vörösmarty (2019) considered inventory-related costs in green supplier selection problems with DEA.

2.4 Summary and identification of research gaps

The highlights of the previous literature showed that recent studies have focused on green supplier selection. In addition, governments have forced companies to consider environmental issues within their decisions. Therefore, as an important section of this area, green supplier section has been properly focussed in previous literature. However, joint supplier selection and order allocation under stochastic demand is less investigated. This paper develops a multi-objective nonlinear programming approach to solve the green supplier selection with multiple sourcing problem and order allocation under stochastic demand. Firstly, a fuzzy analytic hierarchy process (FAHP) is used to weight and rank suppliers. Following, a stochastic multi-objective nonlinear model (MONLP) is developed for the aim of order allocation.

Although green supplier selection has been vastly investigated before, its integration with order allocation under stochastic demand is less investigated. To fill this gap, a FAHP is applied to weight and select suppliers in terms of economic and environmental criteria. Secondly, a MONLP is developed and solved by GA for the aim of order allocation. Regarding the theoretical contribution, the framework of the research, methodology, and outcomes are useful to managers and researchers who are interested in green supplier selection under stochastic demand. This research presents a new idea for incorporation of the green supplier selection and order allocation in the existence of stochastic demand. Overall, to the best of authors' knowledge, this research contributes to provide new visions as no comparable study has been conducted before.

3 Research methodology

In this study, supplier selection and order allocation problems are solved with an integrated FAHP and MONLP. A summary of the research methodology is depicted in Figure 1. This study has been completed in three linked phases as follows.

3.1 Phase 1: Identification of green supplier selection criteria and sub-criteria

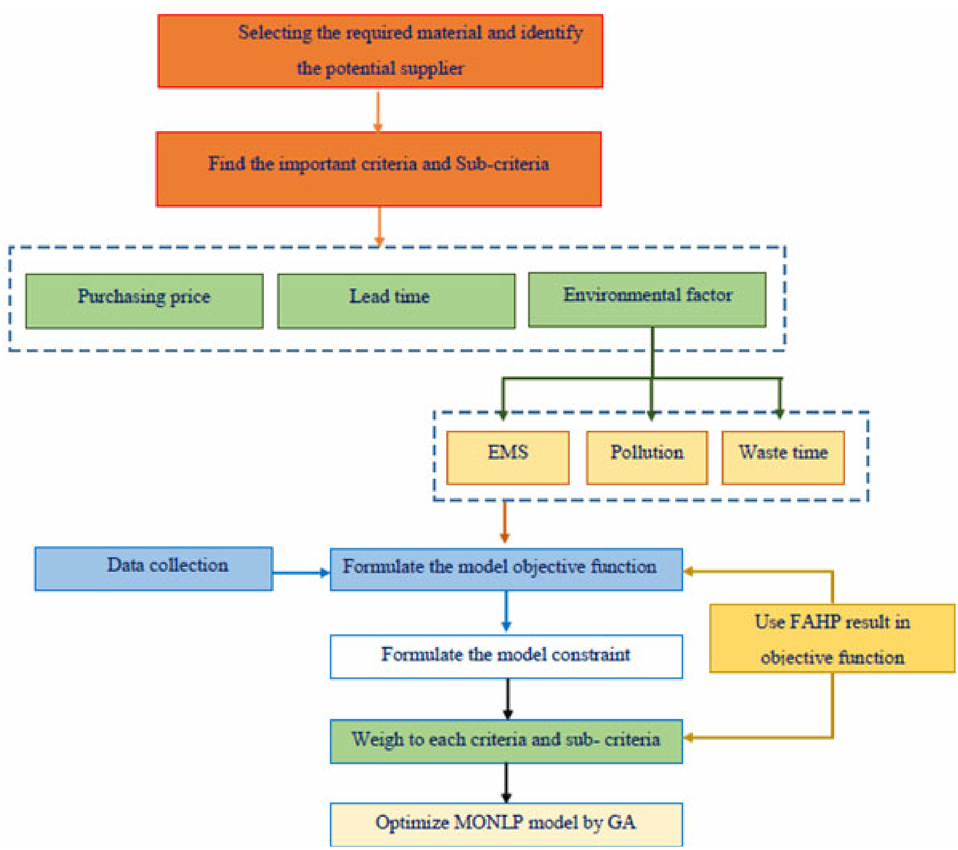
In the first phase, a literature review was conducted to determine the gap of previous studies. In addition, different criteria of green supplier selection were investigated to be used in supplier assessment process. In other words, the criteria and sub-criteria of green supplier selection are identified based on previous literature.

3.2 Phase 2: Supplier selection using FAHP

Supplier selection is an MCDM problem. In this regard, it is necessary to apply MCDM tools to determine the ranking of suppliers with regard to decision-making criteria.

Therefore, initially, the decision-making hierarchy is constructed to determine the final ranking of suppliers. This hierarchy includes four levels as follows. The first level aims to determine the best supplier with regard to green supplier selection criteria. Next, the second level includes the developed criteria to assess the suppliers. Following, the third level includes the sub-criteria of each decision-making criterion. Finally, the fourth level includes the alternatives which are potential suppliers to be assessed from a green viewpoint. Several real world decision-making problems occur in a fuzzy environment. Therefore, using FAHP assists decision-makers to solve the problems with ambiguous data and information. This study has applied the FAHP developed by Chang (1996).

Figure 1 Research framework (see online version for colours)



The following presents the required steps and equation of the FAHP.

1 Classify the supplier selection criteria and sub-criteria, and outline the problem as a hierarchy to cover the decision goal.

2 Determine the pairwise contrast with regard to the relative significance of supplier selection criteria through a geometric mean technique to assimilate the viewpoints of decision makers as follows:

$$R = (a,b,c),\ k = 1,2,...,K\ \ (R: triangular\ fuzzy\ number\ and\ K: no.\ of\ DMs)$$

where, (1)

$$a = \left(a_1 * a_2 * ... * a_k\right)^{1/k},\ b = \left(b_1 * b_2 * ... * b_k\right)^{1/k},\ c = \left(c_1 * c_2 * ... * c_k\right)^{1/k}$$

3 Combine all the decision-makers' matrices of pairwise contrasts and synthesise these judgements to crop a set of overall imports intended for the hierarchy.

4 Do a pairwise evaluation of the relative significance of supplier selection criteria through a geometric mean technique to assimilate the viewpoints of DMs. The judgement is acceptable if the consistency ratio (CR) is less than 0.1.

5 Transform the pairwise assessment matrix of criteria weights into linguistic variables according to Table 1. The main idea of FAHP is to find triangular fuzzy number weights as follows: $X = \{x1, x2, \ldots, xn\}$ is an object set, $G = \{g1, g2, \ldots, gn\}$ is a goal set and $Mgij$ ($i = 1, 2, 3, \ldots, n, j = 1, 2, 3, \ldots, m$) are all triangular fuzzy numbers. The value of the fuzzy synthetic extent of the 'ith' object for the 'm' goal is defined as:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{j=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{2}$$

$$\sum_{j=1}^{m} M_{gi}^{j} = \left[\sum_{j=1}^{m} l_j + \sum_{j=1}^{m} m_j + \sum_{j=1}^{m} u_j\right] \tag{3}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} = \left[\sum_{i=1}^{n} l_i + \sum_{i=1}^{n} m_i + \sum_{j=1}^{n} u_i\right] \tag{4}$$

$$\left[\sum_{j=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i} + \frac{1}{\sum_{i=1}^{n} m_i} + \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{5}$$

The degree of the possibility in which $M2 = (l2, m2, u2) \geq M1 = (l1, m1, u1)$ is defined as:

$$V\left(M_2 \geq M_1\right) = \sup_{x \geq y}\left[\min\left(\mu M_1(x), \mu M_2(y)\right)\right] \tag{6}$$

$$V = \left(M_2 \geq M_1\right) \begin{cases} 1, & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{\left(m_2 - u_2\right)\left(m_1 - l_1\right)} & otherwise \end{cases} \tag{7}$$

The degree of the possibility for a convex fuzzy number to be greater than k convex fuzzy numbers Mi ($i = 1, 2, \ldots, k$) can be defined by: $V(M_1, M_2, \ldots, M_k) = \min V(M \geq M_i)$, which can be defined by:

$$d\left(A_i\right) = \min V\left(S_i \geq S_k\right),\ k = 1,2,...n; k \neq I \tag{8}$$

The weight vector is calculated as:

$$W = \left(d\left(A_1\right), d\left(A_2\right), \ldots, d\left(A_n\right)\right)^T,\ A_i(1, 2, \ldots, n) \tag{9}$$

The normalised weight vector is computed as:

$$NW_i = \frac{w_i}{\sum w_i} \tag{10}$$

Table 1 Linguistic variables for pairwise comparison of each criterion

Linguistic variable	*Fuzzy number*
Extremely strong	(5/2, 3, 7/2)
Very strong	(2, 5/2, 3)
Strong	(3/2, 2, 5/2)
Moderately strong	(1, 3/2, 2)
Equally strong	(1/2, 1, 3/2)
Just equal	(1, 1, 1)

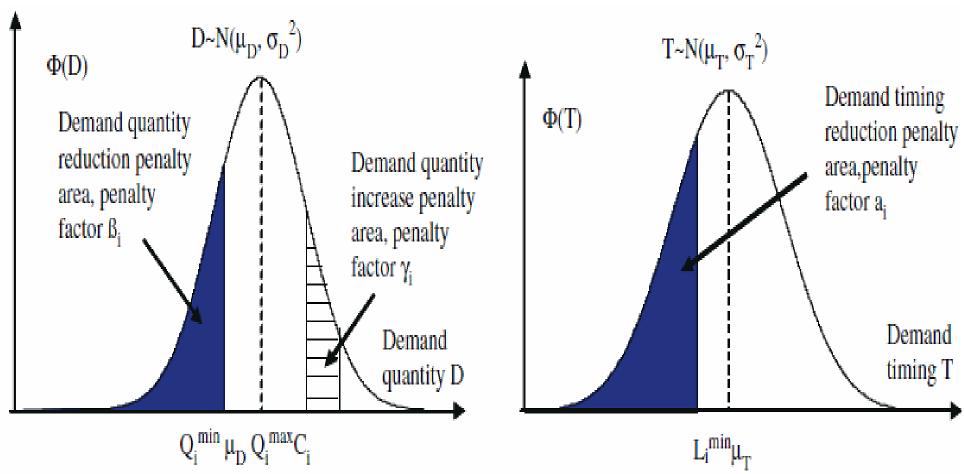
3.3 Phase 3: Model development

Following the supplier selection process, it is necessary to determine the optimum quantity of items to be purchased from each supplier in each period. In other words, as mentioned, the supplier selection and order allocation processes are linked together. Once the companies found the weights of their suppliers with regard to the applied criteria, they have to know about the optimum purchasing plan. As there are numerous objectives in developing the mathematical models, it is necessary to develop multiple-objective decision-making (MODM) approaches to optimise the order allocation. In addition, there are many constraints including the capacity of each supplier in each period to provide the items which makes the application of MODM models necessary. Therefore, an MONLP model is developed to determine the optimum purchasing quantity of each item from each supplier in each period. In addition, a GA is developed to solve the developed MONLP model. The process of model development is discussed as follows.

3.3.1 Model development

An MONLP model is proposed for the aim of order allocation. The proposed model includes a series of goals that must be satisfied simultaneously. This paper develops a MONLP for supplier selection and order allocation problem under stochastic conditions and multiple sourcing. Demand quantity and timing doubts are two most common changes that happen in supply chains. These are also frequent reasons for buyer-supplier complaints (Liao and Rittscher, 2007). In the present case, both demand quantity and demand timing are investigated by normal distribution. Figure 2 illustrates the stochastic conditions of demand quantity and demand timing.

Figure 2 Stochastic demand conditions and flexibility parameters (see online version for colours)



3.3.1.1 Model parameters

The following parameters are applied to formulate the proposed MONLP model of this research:

x_i	Order quantity ratio for supplier i
y_i	Binary decision variable
N	Number of suppliers
D	Stochastic demand quantity satisfying a normal distribution
T	Stochastic demand timing satisfying a normal distribution
C_i	Capacity of supplier i
W^i	Overall weight of supplier i (obtained from the FAHP)
P_i	Unit purchasing price from supplier i
O_i	Ordering cost from supplier i
Tr_i	Unit transportation cost from supplier i
H	Holding cost
Q	Maximum acceptable defect ratio
q_i	Average defect percent from supplier i
W_D	Weight of demand quantity flexibility
W_T	Weight of demand timing flexibility
μ_D	Mean of demand
σD	Standard deviation of demand

Φ (D)	Probability density function of D
μ_T	Mean lead time
σ_T	Standard deviation of lead time
Φ (T)	Probability density function of T
$Q_i^{\min}$	Minimum order quantity; when the order quantity is reduced below $Q_i^{\min}$, the buyer has to pay the supplier a penalty represented by demand quantity reduction penalty (DQRP).
β_i	Maximum DQRP value
$L_i^{\min}$	Minimum supply lead time; when the demand timing schedule is brought forward ahead of $L_i^{\min}$, the demand timing reduction penalty (DTRP) is incurred.
α_i	A proportional rise in unit price due to unit time reduction ahead of $L_i^{\min}$

3.3.1.2 Objective functions

The proposed model includes three objective functions for supplier selection and order allocation as follows:

1 To minimise the total cost of purchasing (TCP).

2 To maximise the total value of purchasing (TVP).

3 To maximise the total flexibility of suppliers (TFS).

The first objective function (Z_1) aims to minimise the TCP. This objective function includes purchasing price, ordering cost, transportation cost, holding cost, and penalty cost (if the firm reduces the ordering quantity below the lower bound of the supplier and requires a shorter delivery time). The proposed model of Liao and Rittscher (2007) was used for expected demand quantity reduction penalty (EDQRP) and expected demand timing reduction penalty (EDTRP) as defined in equation (11) and (12), accordingly. The EDQRP equation is used in the model when $0 \le x_i * D \le Q_i^{\min}$ and the EDTRP equation is used when $0 \le T \le l_i^{\min}$.

$$
\begin{aligned}
Min\ Z_1 = & \sum_{(i=1)}^{N} Pi * \left(x_i * D\right) + \sum_{(i=1)}^{N} O_i * Y_i + \sum_{(i=1)}^{N} TR_i * \left(x_i * D\right) \\
& + H \sum_{(i=1)}^{N} Pi\left(x_i * D/2\right) + EDQRP + EDTRP
\end{aligned}
\tag{11}
$$

$$
EDQRP = \sum_{(i=1)}^{N} \int_{0}^{Q_i^{min}} \left(\left(Q_i^{min} - x_{(i)} * D\right) \Big/ \left(Q_i^{min}\right)\right) * Y_i * \beta_i * \Phi\left(x_{(i)} * D\right) d\left(x_{(i)} * D\right) \tag{12}
$$

$$EDQRP = \sum_{i=1}^{N} Y_{(i)} * \beta_{(i)} * \left\{ \left(1 - \left(x_{(i)} * \mu_D\right) \Big/ \left(Q_i^{min}\right)\right) * \int_0^{Q_i^{min}} \Phi\left(x_{(i)} * D\right) d\left(x_i * D\right) \right.$$
$$+ \left(\left(x_i * \sigma_D\right) \Big/ \left(Q_i^{min} * \sqrt{2\pi}\right) \right. \tag{13}$$
$$\left. \left. * \left[e^{-\left(Q_i^{min} - (x_i * \mu_D)\right)^2 \Big/ 2(x_i * \sigma_D)^2} - e^{-(\mu_D^2 / 2(\sigma_D)^2} \right] \right) \right\}$$

$$EDTRP = \sum_{(i=1)}^{N} \int_0^{l_i^{\min}} \int_0^{Q_i^{\min}} \left(l_i^{\min} - \mu_T\right) * \alpha_i * P_i * x_i * D * \Phi(D) \Phi(T) d(D) d(T) \tag{14}$$

$$EDTRP = \sum_{i=1}^{N} \alpha_i * P_i * x_i * \mu_D \left\{ \left(l_i^{min} - \mu_T\right) \right.$$
$$\left. * \int_0^{l_i^{min}} \Phi(T) * d(T) + \left(\left(\frac{\sigma_T}{\sqrt{2\pi}}\right) * \left[e^{-\left(l_i^{min} - \mu_T\right)^2 \Big/ 2\sigma_T^2} - e^{-\mu_T^2 \Big/ 2\sigma_T^2} \right] \right) \right\} \tag{15}$$

The second objective function (Z_2) aims to maximise the TVP. The weight of each supplier (w_i) is calculated by FAHP. The model is formulated as follows:

$$Max\ Z_2 = \sum_{i=1}^{N} w_i * x_i * D \tag{16}$$

The last objective function (Z_3) aims to maximise the suppliers' flexibility. The model is formulated as follows:

$$\text{Max } Z_3 = \sum_{i=1}^{N} f_i * x_i \tag{17}$$

$$f_i = w_D * \left(1 - \frac{a * \beta_i}{P_i * \mu_D} - \frac{b * Q_i^{\min}}{\mu_D}\right) + w_T * \left(1 - \frac{l_i^{\min} * \sqrt{\alpha_i}}{\mu_T}\right) \tag{18}$$

Constraints of the model are as follows:

- Quality control constraint: the total defect of purchased items must be smaller than the maximum acceptable defect:

$$\sum_{i=1}^{N} q_i * x_i * D \le Q * D \tag{19}$$

- Production demand constraint: total purchased items should satisfy the demand:

$$\sum_{i=1}^{N} x_i * D \geq D \tag{20}$$

- Suppliers' capacity constraint: the order quantity from the *i*th supplier cannot be more than the supplier's capacity:

$$x_i * D \leq C_i \tag{21}$$

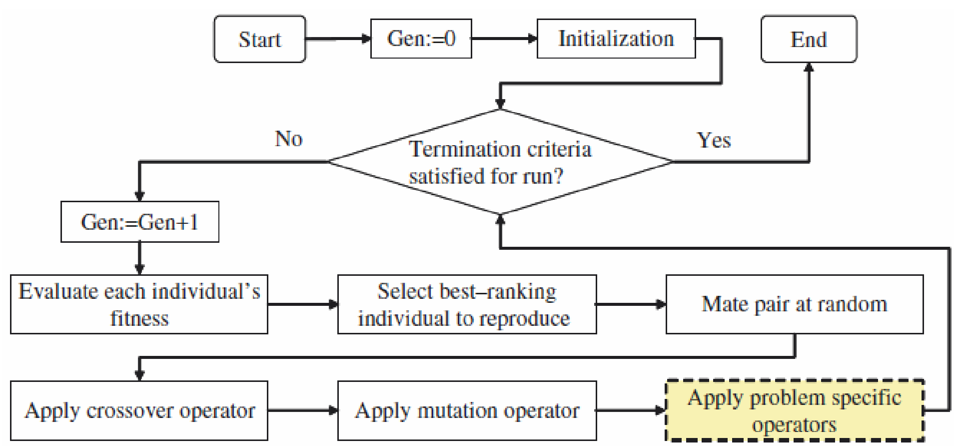
- Decision variables binary constraint:

$$Y_i = \begin{cases} 0 & x_i = 0 \\ 1 & x_i \neq 0 \end{cases} \tag{22}$$

- Non-negativity constraints: the final constraint imposes non-negative restrictions on the decision variables:

$$x_i \geq 0, \quad i = 1, 2, 3, \ldots, n \tag{23}$$

Figure 3 Procedure to run the GA application (see online version for colours)



3.3.1.3 Genetic algorithm

In the proposed model, the TCP (Z_1) is nonlinear, while the total value of purchasing (Z_2) and supplier's flexibility (Z_3) are linear. The x_i results include continuous numbers between 0 and 1 where $\sum_{i=1}^{n} x_i = 1$. As the proposed model is NP-hard, GA approach is applied to solve the model. In addition, the MATLAB software environment is selected to code the model and GA formulations. The program options and parameters of the GA chromosome are defined by genes. The value of each gene in a chromosome represents the ratio selected for each supplier. In this study, three population sizes of 30, 40 and 50 are estimated. In addition, the number of generations for each population size is 100, 150 and 200, to compare the effect of population and number of generations. Parents are chosen between current children and are used to create the next generation. The children of the next generation are 20 from the current elite children and are transferred to the next generation without any change (40% of the population size of 50). The crossover fraction of 0.75 (23 crossover children, or 46% of the population size of 50) is chosen for the next generation and the remaining are mutation children (7 mutation children, or 14% of the population size of 50). The generation number is defined as a stopping condition of the algorithm. Also, both time limit and the stall time limit are infinite. The solution procedure developed by Liao and Rittscher (2007) is applied and presented in Figure 3.

3.4 Case study

A steel baskets manufacturer in Johor Bahru, Malaysia is selected as the case study of this research. This company is one of the largest steel baskets manufacturers in Malaysia and a supplier for big companies all over the world, particularly in the refrigerator industry. Since many successful companies pay more attention to sustainability factors in their processes, company's management decided to improve their sustainability criteria and decrease the environmental pollution. Hence, using green suppliers is an essential requirement to achieve these goals. Economical purchasing cost, supplier lead time, flexibility, product quality, and inventory reduction are other concerns of the company's management. Among all raw materials required by the company, steel is the most important one. Several steel factories can supply the required raw materials. Depending on the demand of each period, the company has different production and purchasing rates. As the result, purchasing manager needs a model to select the best suppliers and identify the optimum purchasing quantities.

In addition to what discussed above, as a developing country, Malaysian companies should follow the environmentally friendly approaches within their processes. In this context, it is very important for the case study to consider the environmental obligations in its purchasing process. As a common criteria, all companies aim to buy their required items with least cost. However, green purchasing is something beyond the sole consideration of cost. In addition, as the case study is not interested in keeping a lot of items in its warehouse, it is obligatory to focus on order allocation also. In other words, according to inventory department of the case study, keeping a lot of items in the warehouse is an important obstacle of the company as it affects its inventory turnover. In addition, as the company does not have an optimum purchasing plan with regard to green consideration, there is no awareness on the exact quantity of required items in each period. The case study aims to satisfy the demand with least cost and a maximised TVP while considering green criteria in supplier assessment process. Therefore, developing a multi-objective mathematical model to determine the optimum purchasing quantity of each item from each supplier in each period assist company's production managers to see all these issues simultaneously.

The criteria and sub-criteria of green supplier selection are developed based on the previous literature. These criteria include unit purchasing price, lead-time and environmental factors. In addition, EMS, pollution and waste are the sub-criteria of environmental factors. For the aim of practical investigation, the initial criteria and sub-criteria were submitted to relevant experts of the company, who have enough knowledge and experience in this area. These experts include the purchasing manager, finance manager, inventory manager, quality assurance manager and logistic manager of the company. Figure 4 presents the hierarchal structure of the decision making process. Furthermore, the company needs to purchase steel from four suppliers. The purchasing data of this item (steel) is investigated in this research. All required purchasing data are collected from the company's purchasing management team. As this study required both quantitative and qualitative data to solve the supplier selection problem, the qualitative data was used in FAHP to weigh each supplier. The survey form was submitted to the purchasing management team and the experts were asked to use a six-point preference scale (from extremely strong to just equal) to determine the pairwise importance of preference for the criteria and sub-criteria and compare suppliers. Triangular fuzzy numbers were applied to calculate the input data of FAHP. The required quantitative data were gathered from the suppliers.

3.5 Data collection and framework validation

As discussed, this research has been completed in three phases. The related criteria and sub-criteria of green supplier selection are developed based on previous literature. Following, the second phase aims to select the suppliers using a FAHP approach. Therefore, this phase includes the first data collection process of this research. To do so, a questionnaire is designed and the experts were asked to fill it accordingly. The developed questionnaire includes four sections as follows. The first sections asked the experts to provide some general information on their age, education, background and the working experiences. The second section provides the pairwise comparison of criteria. This section is followed by the third section which includes the pairwise comparison of sub-criteria. Finally, the last section compares suppliers based on the developed sub-criteria. Regarding the last phase of this research, as mentioned, this phase develops a mathematical model to determine the optimum purchasing quantity of each item from each supplier in each period. In this regard, the second data collection process includes the required data of each parameter of the mathematical model. This data collection process is completed in the case study which is discussed in previous section. Regarding the validation, as this research has applied two questionnaires for the aim of developing the measures and completing the FAHP calculations, the developed questionnaires were checked by some experts to be validated. In addition, the contents of questionnaires were examined to be error free and gather what the authors need for calculations. However, as the questionnaires were filled in the presence of the data collector (first author), any misunderstanding and questions of the experts could be handled easily. In addition, regarding the collected data, the company provided accurate data as the outputs could be beneficial for the company. In addition, to address the validity of the framework, the obtained results of all phases were discussed with the production managers of the company. According to the meetings, the managers approved that even minor corrections of production process, supplier selection and other related issues with regard to green concerns could be beneficial to sustain the environment and move toward the green manufacturing. In addition, the obtained results of the mathematical model are validated as no error is occurred in the process of solving the model.

3.6 Contributions of the research methodology

As discussed, this study develops an integrated approach for green supplier selection and order allocation. The developed methodology includes the development of green supplier selection criteria, supplier selection by FAHP, model development for order allocation and finally the model solution procedure to achieve the optimum purchasing quantities from the developed model. The main contribution of the developed methodology includes the development of green supplier selection measures, application of FAHP in green supplier selection problem, developing a stochastic model and finally the GA application in solving the model. Similar to previous studies on this topic, the measures, model and solution approach are developed to be applied in a specific problem. In other words, the outputs of this research are developed from the previous literature. However, the model development and the suggested solution approach is novel as these equations might be applied in other research topics. Therefore, in summary, the measures are developed from previous literature, the FAHP technique is adopted from Chang (1996) and finally the developed model and solution technique are developed based on previous literature.

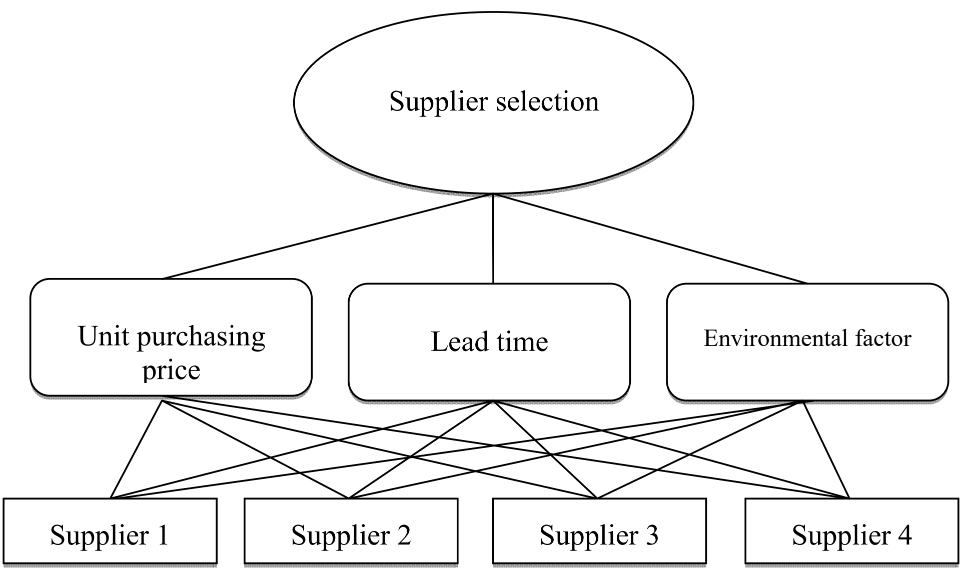
4 Results

This section discusses the obtained results of this research.

4.1 FAHP methodology for weighs of criteria

Figure 4 presents the hierarchical structure of the criteria and decision problem of this study.

Figure 4 Hierarchical structure of the decision problem



The purchasing manager and decision-makers of this company conducted pairwise comparisons in order to evaluate the weights of each criterion. The pairwise comparison matrices are presented in Tables 2 to 8.

Table 2 Importance of preference for one main criterion over another with respect to the overall goal

Criteria	*Unit purchasing price*	*Lead time*	*Environmental factor*
Unit purchasing price	(1,1,1)	(1,3/2,2)	(1/2,1,3/2)
Lead time	(1/2,2/3,1)	(1,1,1)	(2/3,1,2)
Environmental factor	(2/3,1,2)	(1/2,1,3/2)	(1,1,1)

Table 3 Importance of preference for one sub-criterion over another in terms of environmental factors

Environmental factor	*Environmental management system (EMS)*	*Pollution*	*Waste*
Environmental management system (EMS)	(1,1,1)	(1/2,1,3/2)	(3/2,2,5/2)
Pollution	(2/3,1,2)	(1,1,1)	(1,3/2,2)
Waste	(2/5,1/2,2/3)	(1/2,2/3,1)	(1,1,1)

Table 4 Importance of preference for one supplier over another in terms of cost

Unit purchasing price	*Supplier 1*	*Supplier 2*	*Supplier 3*	*Supplier 4*
Supplier 1	(1,1,1)	(1,3/2,2)	(2/3,1,2)	(3/2,2,5/2)
Supplier 2	(1/2,2/3,1)	(1,1,1)	(2/5,1/2,2/3)	(1/2,1,3/2)
Supplier 3	(1/2,1,3/2)	(3/2,2,5/2)	(1,1,1)	(2,5/2,3)
Supplier 4	(2/5,1/2,2/3)	(2/3,1,2)	(1/3,2/5,1/2)	(1,1,1)

Table 5 Importance of preference for one supplier over another in terms of lead time

Lead time	*Supplier 1*	*Supplier 2*	*Supplier 3*	*Supplier 4*
Supplier 1	(1,1,1)	(2/3,1,2)	(1,3/2,2)	(1,1,1)
Supplier 2	(1/2,1,3/2)	(1,1,1)	(3/2,2,5/2)	(1/2,1,3/2)
Supplier 3	(1/2,2/3,1)	(2/5,1/2,2/3)	(1,1,1)	(1/2,2/3,1)
Supplier 4	(1,1,1)	(2/3,1,2)	(1,3/2,2)	(1,1,1)

Table 6 Importance of preference for one supplier over another in terms of EMS

EMS	*Supplier 1*	*Supplier 2*	*Supplier 3*	*Supplier 4*
Supplier 1	(1,1,1)	(3/2,2,5/2)	(1/2,1,3/2)	(1,3/2,2)
Supplier 2	(2/5,1/2,2/3)	(1,1,1)	(1/2,2/3,1)	(2/3,1,2)
Supplier 3	(2/3,1,2)	(1,3/2,2)	(1,1,1)	(1/2,1,3/2)
Supplier 4	(1/2,2/3,1)	(1/2,1,3/2)	(2/3,1,2)	(1,1,1)

Table 7 Importance of preference for one supplier over another in terms of pollution

Pollution	*Supplier 1*	*Supplier 2*	*Supplier 3*	*Supplier 4*
Supplier 1	(1,1,1)	(1/2,1,3/2)	(1/2,2/3,1)	(2/3,1,2)
Supplier 2	(2/3,1,2)	(1,1,1)	(2/5,1/2,2/3)	(1/2,2/3,1)
Supplier 3	(1,3/2,2)	(3/2,2,5/2)	(1,1,1)	(1/2,1,3/2)
Supplier 4	(1/2,1,3/2)	(1,3/2,2)	(2/3,1,2)	(1,1,1)

Table 8 Importance of preference for one supplier over another in terms of waste

Waste	*Supplier 1*	*Supplier 2*	*Supplier 3*	*Supplier 4*
Supplier 1	(1,1,1)	(1,3/2,2)	(1/2,1,3/2)	(2/3,1,2)
Supplier 2	(1/2,2/3,1)	(1,1,1)	(2/3,1,2)	(1/2,2/3,1)
Supplier 3	(2/3,1,2)	(1/2,1,3/2)	(1,1,1)	(2/3,1,2)
Supplier 4	(1/2,1,3/2)	(1,3/2,2)	(1/2,1,3/2)	(1,1,1)

Based on Chang's method and equations (1) to (10), the weight of each supplier is calculated as follows:

$$\begin{aligned}\text{The weight of supplier } 1 &= (0.34*0.37)+(0.275*0.30)+(0.31*0.44*0.33)\\ &\quad+(0.23*0.39*0.33)+(0.27*0.17*0.33)=0.298\end{aligned}$$

$$\begin{aligned}\text{The weight of supplier } 2 &= (0.13*0.37)+(0.30*0.30)+(0.19*0.44*0.33)\\ &\quad+(0.19*0.39*0.33)+(0.21*0.17*0.33)=0.202\end{aligned}$$

$$\begin{aligned}\text{The weight of supplier } 3 &= (0.40*0.37)+(0.15*0.30)+(0.27*0.44*0.33)\\ &\quad+(0.31*0.39*0.33)+(0.25*0.17*0.33)=0.286\end{aligned}$$

$$\begin{aligned}\text{The weight of supplier } 4 &= (0.13*0.37)+(0.275*0.30)+(0.23*0.44*0.33)\\ &\quad+(0.27*0.39*0.33)+(0.27*0.17*0.33)=0.214\end{aligned}$$

4.2 Supplier quantitative data

The proposed nonlinear model requires each parameter data to find the solution. The supplier weights are determined by FAHP. The demand quantity and time are not constant for entire periods. Moreover, both stochastic demand quantity and timing are satisfied based on the normal distribution. Related information of the model parameters are tabulated in Table 9. Also, the required data of the suppliers are presented in Table 10.

Table 9 Model parameters

Item	N	μ_D	σ_D	μ_T	σ_T	Q	H	W_D	W_T	a	b	D	T
Value	4	60000	11000	4	1.5	0.5%	0.03	0.6	0.4	0.4	0.3	60000	2

Table 10 Information of company's suppliers

Supplier candidates (S_i)	S_1	S_2	S_3	S_4
Purchasing price (p_i)	2.5	2.85	2.30	2.95
Ordering cost (O_i)	50	50	50	50
Transportation cost (TR_i)	0	0	0	0
Min. order quantity ($Q_i^{\min}$)	20000	15000	20000	35000
DQRP factor (β_i)	500	500	600	650
Min. supplier lead time ($L_i^{\min}$)	3	2.5	4	3

Table 10 Information of company's suppliers (continued)

Supplier candidates (Si)	S_1	S_2	S_3	S_4
DTRP factor (α_i)	0.09	0.10	0.09	0.11
Capacity (C_i)	35000	40000	30000	50000
Quality rejection rate (%) (q_i)	0.1	0.2	0.1	0.3
Supplier weight	0.298	0.202	0.286	0.214
Flexibility rate (%) (f_i)	77.64	79.47	74.89	71.94

5 Discussions

Supplier selection decisions are made by simultaneous consideration of total cost, quality rejection rate, late delivery rate, environmental factors, adaptability rate under stochastic demand quantity and timing conditions. The flexibility of current suppliers is calculated by equation (18) and the results are S_1 = 84.9%, S_2 = 87.6%, S_3 = 81.9% and S_4 = 79.5%, respectively. As it is clear, S_2 is the most flexible supplier while the worst one is S_4. These flexibility results are important for the third objective function (Z_3). In addition, based on the FAHP results, $W_{s1} = 0.298$, $W_{s2} = 0.202$, $W_{s3} = 0.268$ and $W_{s4} = 0.214$, where S_1 and S_4 showed the highest and lowest weights among current suppliers, respectively. Figure 5 indicates the FAHP results and total weight of each supplier. The weights of the suppliers are important for calculating TVP (Z_2). Three independent experiments with different population sizes and number of generations are performed as the obtained results are indicated in Table 11.

Figure 5 Suppliers' total weights (see online version for colours)

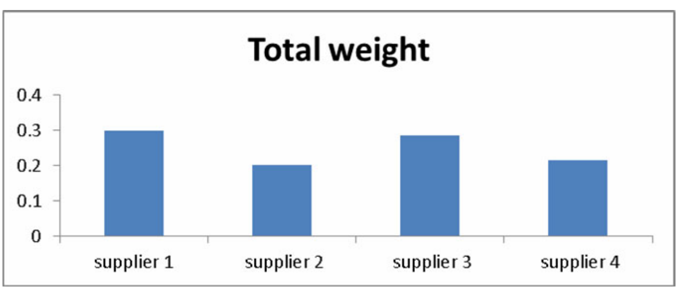


Table 11 Amount of xi for each supplier and the fitness values

Population and generation	x_1	x_2	x_3	x_4	*F-value*
Population = 30 Generation =100	0.5232	0.1045	0.3713	0.0000	138003.4257
Population = 40 Generation =150	0.4648	0.2212	0.3140	0.0000	140863.8303
Population = 50 Generation =200	0.5397	0.1118	0.3485	0.0000	137847.6545

All three objective functions of Z_1, Z_2 and Z_3 were combined as one objective function and were solved in a downscale situation. Consequently, based on the information shown in Table 11, the best (minimum) fitness value occurred when the population size and the generation size were 50 and 200, respectively. To be more precise, in this purchasing period, the demand quantity is 60000 KG and the lead time is satisfied for over two weeks. The GA optimum solution was achieved when the purchasing ratio from Supplier 1 was 53.97%, the purchasing ratio from Supplier 2 was 11.18%, the purchasing ratio from Supplier 3 was 34.85% and there was no purchase from Supplier 4. In the first experiment (population = 30, generation = 100), the quantity of x_1 is equal to 52.32%, x_2 is equal to 10.45%, x_3 is equal to 37.13% and x_4 is equal to 0.0%. In the second experiment (population = 40, generation = 150), x_1 is equal to 46.48%, x_2 is equal to 22.12%, x_3 is equal to 31.40% and x_4 is equal to 0.0%. Figures 6 and 7 illustrate the best function value versus the generations for xi when the population size is 30 and 40 and the generations are equal to 100 and 150, respectively. Figure 8 presents the best function value versus the generation of x_i when the population size and generation are 50 and 200, respectively. Based on Figures 6 to 8, it can be deduced that the effect of population is greater than generations, since the fitness value fluctuation get smaller considerably after ten generations.

Figure 6 Fitness function values versus generations (see online version for colours)

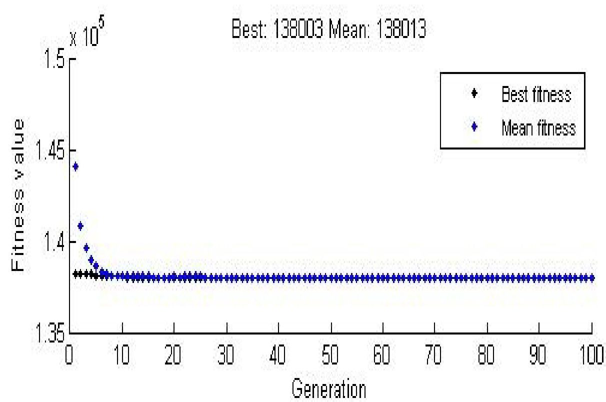


Figure 7 Fitness function values versus generations (see online version for colours)

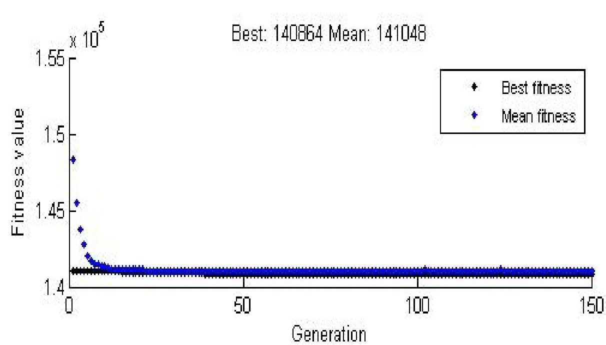


Figure 8 Fitness function values versus generations (see online version for colours)

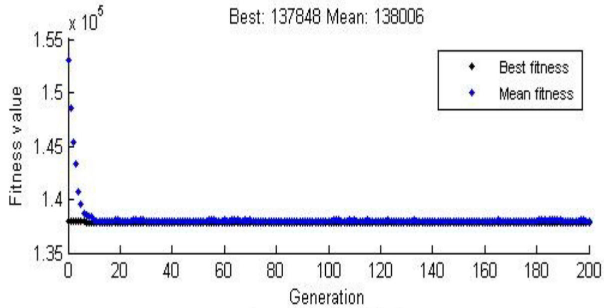
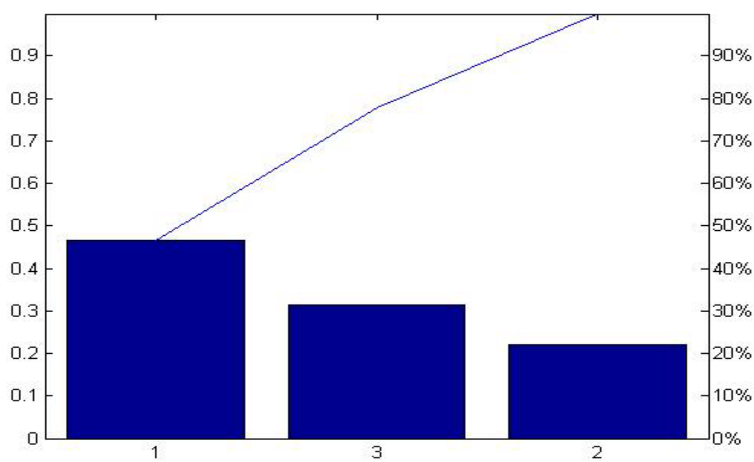


Figure 9 illustrates the Pareto chart of x_i. Based on Figure 9, the highest purchasing amounts are related to S_1, S_3, and S_2, respectively. There is no purchase from S_4 and therefore it is not shown in Figure 9. S_1 is the second most flexible supplier with the highest weight due to appropriate green factors and cheapest price. S_2 has the highest flexibility, lowest weight and ranked at the third supplier regarding the selling price of steel. S_3 has the lowest price, second highest weight and third best flexibility. S_4 has the most expensive products, lowest flexibility and does not fulfil the green factors. Therefore, this section showed the effect of cost, quality, lead time, green environmental factors and supplier flexibility on supplier selection and order allocation problem.

Figure 9 Pareto chart for x_i (see online version for colours)



6 Sensitivity analysis

This section provides the sensitivity analysis of the paper. To do so, different parameters of the model are modified and the new outputs are shown in Figures 10 to 13. Figure 10 displays the effect of different weights on decision variables. According to this figure, the amount of the first decision variable is decreased first, kept to be steady and finally decreased at the last stage. Regarding the second decision variable, its value has been steadily increased. However, the slope of this increment is not very significant. Following, the third decision variable is slightly increased first and decreased in the following stages. Finally, the last decision variable's values are zero. Figure 11 shows the effect of different weights on objective function. According to this figure, the value of objective function is sharply increased first, kept to be steady and is sharply increased in the last phase. The effect of different values of p_i on decision variables is shown in Figure 12. As it is shown, the value of the first decision variable is increased. Reversely, the value of second decision variable is sharply decreased. The third decision variable is slightly increased while no change is occurred in the last decision variable. Finally, Figure 13 displays the effect of different values of p_i on objective function. As shown, the value of objective function is sharply increased and then slightly decreased.

7 Managerial implications

This study provided a mathematical model for green supplier selection and optimum order allocation under a fuzzy environment and stochastic condition. The employed fuzzy environment made the model more realistic. In addition, the applied multi-objective model assists managers to make the supplier selection decision with different priorities and order quantities. The proposed model of this study reduces the raw material purchasing risk since multiple factors are included in the decision. Reduced cost of purchasing, improved quality, increased supplier flexibility, lower lead time and considered environmental factors help managers to improve their competitive ability in the market.

Figure 10 The effect of different weights on decision variables (see online version for colours)

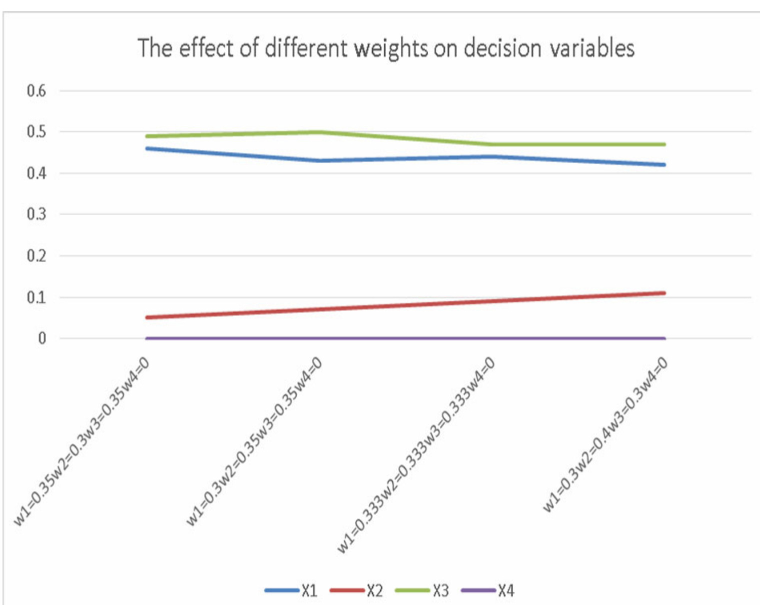


Figure 11 The effect of different weights on objective function (see online version for colours)

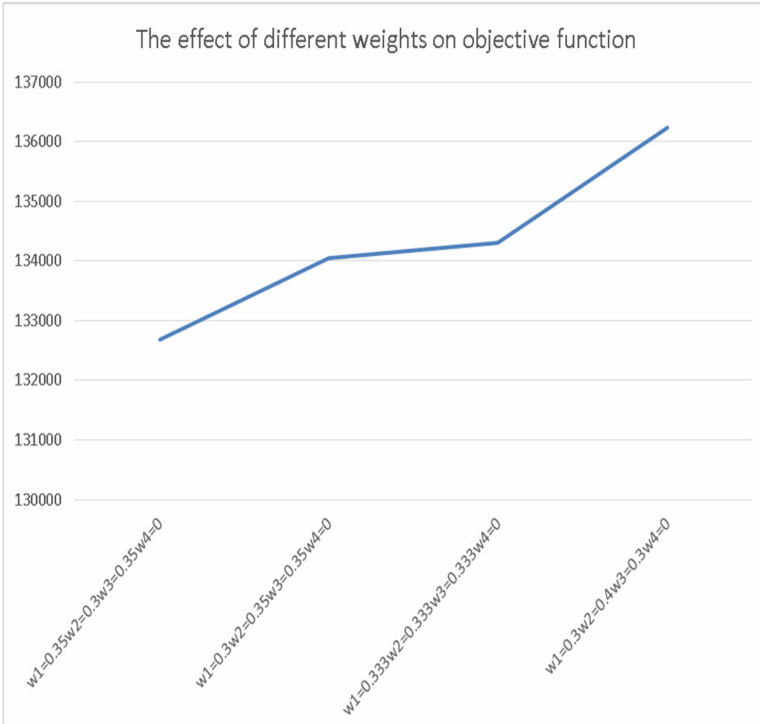


Figure 12 The effect of different values of p_i on decision variables (see online version for colours)

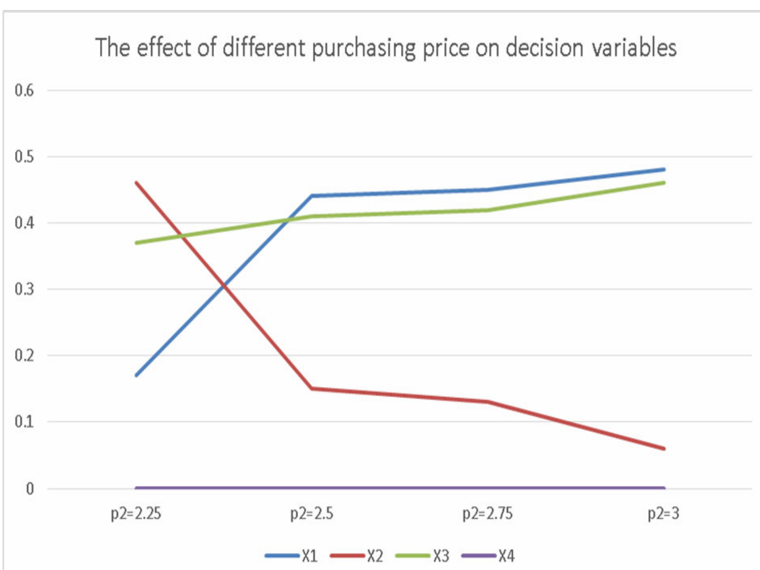


Figure 13 The effect of different values of p_i on objective function (see online version for colours)

8 Conclusions

Supplier selection and optimum order allocation under stochastic and green supply chain conditions were the addressed problems of this study. Supplier selection is a MCDM issue which plays an important role in supply chain management. Both qualitative and quantitative data are involved in this procurement decision of supply chain. For this reason, this study used FAHP to cover qualitative data and a MONLP model to consider the quantitative data. The stochastic conditions of the demand quantity and timing assist purchasing managers to make decision in a real world environment.

This research provided a case study to analyse the supplier selection and environmental factors, simultaneously. The results of the mathematical model indicated the effect of each factor on the optimum order quantity of existing suppliers. These results presented the purchasing ratio of each supplier and best fitness function value of purchasing periods. In conclusion, this mathematical model assists companies to select suppliers with regard to environmental considerations, least cost and maximised customers' satisfaction. Similar to all previous studies, this research also faced some limitations. As a direction for future research, using larger population size and generations to solve the proposed model is recommended. Correspondingly, future researchers may focus on other qualitative criteria and sub-criteria, especially green (environmental) factors in the second objective function. In addition, other solution approaches could be proposed to solve the model.

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