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An Integrated Approach for Sustainable Supplier Selection in Fuzzy Environment

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Abstract: The term sustainability, which means maintaining a balance or acting responsibly for the future, has come into prominence in many fields. One of the most crucial practice is cooperating with convenient collaborators and composing effective supply chains in terms of social, economic and environmental considerations. Therefore, sustainable supplier selection is getting more and more important to compete in rapidly changing environment. To deal with sustainable supplier selection problem, this study aims to determine the selection of appropriate suppliers and allocation of orders to them. The proposed approach operates in three stages. In the first stage, Fuzzy Decision Making Trial and Evaluation Laboratory is used to obtain the weights of the criteria from sustainability perspective. In the second stage, by using Fuzzy Grey Relational Analysis, a set of suppliers are ranked and their suitability scores are calculated. In the last stage, optimal order quantities to be procured by the suppliers are obtained via fuzzy linear programming including imprecise data of demand, error rate and capacity.

Keywords: *Sustainable supplier selection, Fuzzy logic, DEMATEL, Grey relational analysis, Fuzzy linear programming.*

1. Introduction

Nowadays, it has been obligatory to analyse customers' requirements precisely and meet demand in short time. While meeting demand, the production technology should also be considered and improved to gain flexibility in production processes. Moreover, the limited resources of the world should be utilized effectively considering the future. In 1987, sustainable development was clearly defined as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" by World Commission on Environment and Development [1]. It helped to mould the international attitude and to raise the awareness of sustainability and its dimensions. Consequently, companies should make the decisions considering economic dimension of sustainability as well as social and environmental dimensions. Sustainable supplier selection problem, the main topic of our study, means to select the suppliers in an effective way to provide sustainability with all dimensions.

With the increase in the awareness of sustainability, the sustainable supplier selection problem has received a lot of attention in recent years. However, nearly all studies focusing on this problem, have only addressed to determine the best suppliers. In some cases, it is necessary to determine size of orders that should be allocated to these suppliers as well. Based on literature review, there are a few studies considering both selecting suppliers and determining order sizes in sustainable supplier selection literature. To fill this gap, this study proposes an integrated approach. The proposed approach first determines the appropriate suppliers and then order sizes.

The rest of the study is organized as follows. In section two, a literature review on the relevant subject is presented. In section three, the problem and proposed approach are explained. The implementation of the proposed methodology is illustrated in section four. In the last section, the paper is concluded with some future research directions.

2. Literature Review

In today's highly competitive business life, profitability of the company has direct relation with its own source consumption and internal productivity, as well as the effectivity of the overall supply chain. Therefore, supplier selection and performance evaluation are the key elements for composing effective supply chains. In the literature, numerous studies have addresses the solution of supplier selection problem. The problem includes more than one criterion and with this aspect, it is an example of multi criteria decision making (MCDM) problems. Therefore, different MCDM methods have been applied.

Sustainable supplier selection has been a prominent topic since the middle of 1990s. Brandenburg et al. [2] and Zimmer et al. [3] reviewed the literature of the mathematical models for sustainable supplier management in detail. They also summarized the sustainable supplier management approaches into two groups such as integrated models and single models which consist of qualitative, mathematical programming, mathematical analytical, artificial intelligence [3]. Azadi et al. [4] and Yousefi et al.[5] applied robust dynamic and fuzzy data envelopment analysis method for sustainable supplier selection problem. An optimization model using binary integer programming for simultaneous supplier selection and development was proposed by Trapp and Sarkis [6]. Orji and Wei [7] added the time dimension to decision making process and suggested a dynamic framework consisting of system dynamics and simulation for selecting appropriate suppliers considering sustainability factors.

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The results of the proposed approach were compared to the results derived from TOPSIS method. Incomplete information throughout the decision making process was considered in Su et al. [8] and an integrated approach consisting of grey theory and DEMATEL was proposed to compensate incomplete information. Amindoust et al. [9] and Ghadimi and Heavey [10] implemented fuzzy inference system to determine the suitable suppliers. Azadnia et al. [11] proposed an integrated approach based on fuzzy AHP, neural networks, clustering and TOPSIS. Another integrated approach was proposed by Shaw et al. [12] using fuzzy AHP to calculate the weights of the criteria and fuzzy multi-objective linear programming model to allocate the orders. Büyüközkan and Çifçi [13] developed an integrated methodology using fuzzy ANP, DEMATEL and TOPSIS for sustainable supplier evaluation and selection. Bai and Sarkis [14] suggested a supplier evaluation model based on rough set theory and grey system theory to deal with the information vagueness.

The literature review has stated that the importance of sustainable supplier selection problem has increased recently. To find a solution to this problem, most studies have focused on integrated approaches instead of single models. Nearly all studies have focused on only selecting the best suppliers. However, supplier selection problem also inherits the order allocation phase in which order sizes are determined. The literature review shows that the number of studies focusing on both supplier selection and order allocation is rather limited. Another assessment from the review is that fuzziness and vagueness in decision making process is substantially taken into consideration. Motivated from these inferences, an integrated fuzzy approach is proposed for determining appropriate suppliers and order sizes. The proposed approach first determines the appropriate sustainable suppliers and then allocates the orders to these suppliers. The details are given in the following section.

3. The Proposed Integrated Methodology

This study integrates fuzzy DEMATEL, fuzzy grey relational analysis and fuzzy linear programming to solve sustainable supplier selection problem and operates in three stages. In the first stage, we used fuzzy DEMATEL to calculate the weights of the criteria. In the second stage, fuzzy grey relational analysis was used to rank suppliers according to sustainability dimensions. In the third stage, the weights of the suppliers which were calculated in the previous stages, were incorporated into the fuzzy linear programming model to obtain the optimum order sizes of the appropriate suppliers. The main steps of the proposed integrated approach are shown in Fig.1.

4. A Case Study

In this section, the illustration of the proposed model is shown. This study particularly focuses on the sustainable supplier selection problem of an online retailer store located in Canada that works with different travertine-marble suppliers located in Turkey. Recently, it needs to search for sustainable, reliable and constant suppliers due to the problems about orders faced with the previous suppliers. Within this scope, three most demanded products and four possible suppliers are determined. Before the application of the proposed approach, the criteria, which are used for supplier selection considering sustainability factors, are determined. Therefore, the criteria are determined based on triple bottom line [15] and explained in Table 1.

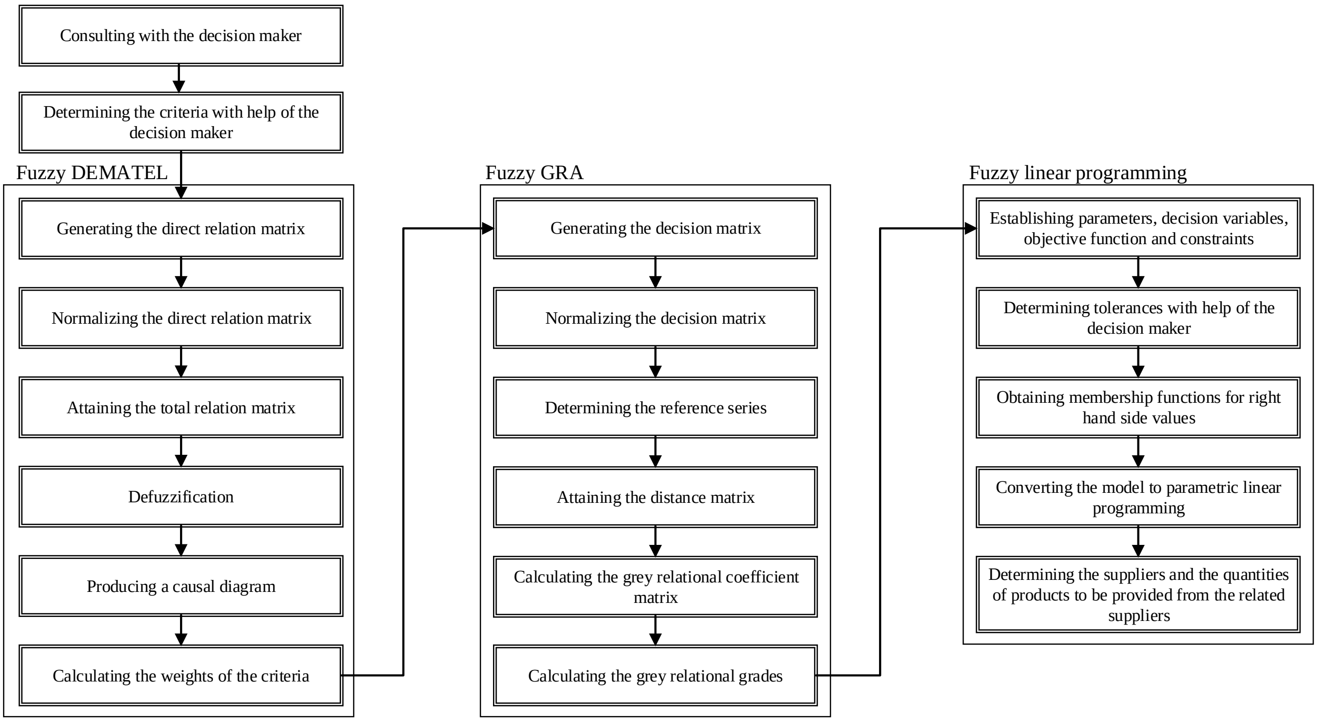

Figure 1. The proposed methodology

Table 1. Criteria used in this study

Economic criteria [16]	
C_1 - Cost	Companies always want to supply required materials with minimum cost. This criterion lets the company rank the suppliers based on sale prices of their products.
C_2 - Productivity	Productivity is related to percentage of the product obtained from given amount of raw material.
C_3 - Capacity	This criterion shows the degree of compensation of given orders. In order to satisfy the company's needs, the suppliers should have enough capacity.
C_4 - Continuity	Suppliers should have a close relationship with companies. The continuity criterion shows the degree of relationship between supplier and the company.
C_5 - Lead time	The lead time is the time between the time the order is initiated and the time it is delivered. This criterion is related to supply any amount of item from supplier to the company when company need raw materials or products.
C_6 - Quality	The degree of matching the customers' requirements of ordered products or raw materials can be illustrated as the quality criterion.
C_7 - Production technology	The production technology of a supplier is crucial in the evaluation process. With new technologies, it is possible to respond customers' orders quickly. Therefore, the company would rather prefer working with suppliers having new technologies than working with suppliers having old technologies.
C_8 - Responsiveness	This criterion is related to communication, knowledge sharing and tracing activities provided by the supplier between the time the order is initiated and the time it is delivered.
Social criteria [11]	
C_9 - Occupational health and safety management system	Companies should provide safer working place for their employees. This criterion shows the degree of safety regulations carrying out throughout the working place.
C_{10} - Training education	This criterion states that the training education which is given to all recruiting employees including managers.
Environmental criteria [17]	
C_{11} - Environmental management system	Environmental certifications like ISO 14000, environmental policies, planning, checking and control of environmental activities are all considered under this criterion.
C_{12} - Environmental friendly product design	This criterion shows that production process is performed with lower energy and material consumption.
C_{13} - Resource consumption	The degree of effective usage of resources during the production process, the percentage of renewable energy and material usage for production can be defined as resource consumption criterion.

4.1. Fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) Implementation

DEMATEL method is mainly based on graph theory and was conducted by Geneva Research Centre of the Battelle Memorial Institute [18]. DEMATEL is a comprehensive method for building and analysing a structural model involving causal relationships between complex factors [8]. This aspect helps the decision maker to reveal and visualize the interdependence relationships between criteria and sub-criteria. Furthermore, it lets the decision process conclude relatively easily and reliably. The basic steps and application of fuzzy DEMATEL method is described as follows.

Each criterion, which is determined based on sustainability dimensions, is written throughout columns and rows. Elements of the matrix show the pairwise comparison values of the criteria and are determined by means of linguistic variables. In this part, the linguistic scale shown in Table 2 was used.

Table 2. Linguistic scale [19]

Linguistic variable (effect)	Value	Triangular fuzzy number
No - N	0	(0,0, 1/4)
Very low - VL	1	(0,1/4,1/2)
Low - L	2	(1/4,1/2,3/4)
High - H	3	(1/2,3/4,1)
Very high - VH	4	(3/4,1,1)

The direct relation matrix (A) is established according to the expert's remarks and shown as follows.

$$A = \begin{pmatrix} 0 & 0 & VL & VL & H & H & VL & H & 0 & L & VL & L & VL \\ H & 0 & 0 & H & H & H & 0 & H & 0 & VL & 0 & VL & H \\ 0 & 0 & 0 & L & VH & 0 & 0 & VH & 0 & 0 & 0 & 0 & H \\ L & L & VL & 0 & H & 0 & 0 & H & VL & L & VL & VL & L \\ 0 & 0 & 0 & H & 0 & VL & 0 & VL & 0 & 0 & VL & L & H \\ H & 0 & 0 & H & VL & 0 & 0 & 0 & 0 & L & L & VL & VL \\ H & H & VH & H & L & VH & 0 & L & L & L & L & VL & VH \\ 0 & 0 & 0 & VH & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ VL & VL & 0 & L & 0 & VL & 0 & 0 & 0 & VL & VL & VL & L \\ VL & VL & 0 & L & 0 & VL & 0 & 0 & VL & 0 & VL & VL & VL \\ VL & 0 & 0 & H & 0 & L & 0 & 0 & H & L & 0 & L & H \\ H & VL & 0 & H & L & VL & 0 & 0 & L & VL & VL & 0 & H \\ H & H & L & L & VL & VL & 0 & 0 & VL & 0 & H & VL & 0 \end{pmatrix} \quad (1)$$

The normalized direct relations matrix is obtained [20] and shown partly in Eq. (2).

$$\tilde{A}^* = \begin{pmatrix} (0, 0, 0) & (0, 0, 0.02381) & \cdots & (0, 0.032258, 0.047619) \\ (0.105263, 0.096774, 0.095238) & (0, 0, 0) & \cdots & (0.105263, 0.096774, 0.095238) \\ \vdots & \vdots & \ddots & \vdots \\ (0.105263, 0.096774, 0.095238) & (0.105263, 0.096774, 0.095238) & \cdots & (0, 0, 0) \end{pmatrix} \quad (2)$$

Once the normalized direct relation matrix is obtained, the total relation matrix is established [20]. Total relation matrix can be separated into separate sub matrices i.e., (X_l, X_m, X_u) to overcome the following defuzzification process easily. To illustrate this step, Eq. (3) is given which includes X_l and T_l matrices.

$$X_l = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ 0.105263 & 0 & \cdots & 0.105263 \\ \vdots & \vdots & \ddots & \vdots \\ 0.105263 & 0.105263 & \ldots & 0 \end{pmatrix}$$

$$\ldots\ldots \quad . \quad (3)$$

$$T_l = \begin{pmatrix} 1.0237 & 0.005325 & \cdots & 0.023358 \\ 0.145912 & 1.023396 & \cdots & 0.13664 \\ \vdots & \vdots & \ddots & \vdots \\ 0.132011 & 0.114954 & \cdots & 1.041973 \end{pmatrix}$$

Several methods can be used for defuzzification process but we adopted an extensive defuzzification method of converting fuzzy data into crisp scores (CFCS) which was introduced by Opricovic and Tzeng [21]. The steps of defuzzification process consist of normalization, right and left hand side normalized values, total normalized value and crisp values. The application of defuzzification illustrated partly in Table 3.

The next step includes calculating the sum of rows and the sum of columns separately denotes as vectors D and R within the total relation matrix. The weights of the criteria are obtained via D and R values [20] and shown in Table 4.

Table 3. Defuzzification table via CFCS method [21]

	Triangular fuzzy numbers			Normalization						Right and left hand side normalized values		Total normalized values	Crisp values
	l	***m***	***u***	***min l***	***max u***	***Δ***	***x l***	***x m***	***x u***	***x ls***	***x rs***	***x***	***z***
C_1	1.024	1,050	1,111	0	1.144	1.144	0.895	0.918	0.972	0.897	0.922	0.920	1.052
C_2	0.146	0.151	0.210	0	1.144	1.144	0.128	0.132	0.184	0.131	0.175	0.139	0.159
C_3	0.024	0.028	0.108	0	1.144	1.144	0.021	0.025	0.094	0.024	0.088	0.030	0.034
…	...	...	...	...	...	...	...	...	...	...	…	…	…
C_{13}	1.042	1.069	1.123	0	1.144	1.144	0.911	0.934	0.988	0.913	0.938	0.936	1.070

Table 4. Weights of the criteria

Criteria	Weights of the criteria	Criteria	Weights of the criteria
C_1 - Cost	0.084	C_8 - Responsiveness	0.066
C_2 - Productivity	0.077	C_9 - Occupational health and safety management system	0.064
C_3 - Capacity	0.063		
C_4 - Continuity	0.097	C_{10} - Training education	0.067
C_5 - Lead time	0.077	C_{11} - Environmental management system	0.075
C_6 - Quality	0.075	C_{12} - Environmental friendly product design	0.077
C_7 - Production technology	0.087	C_{13} - Resource consumption	0.091

4.2. Fuzzy Grey Relational Analysis (GRA) Implementation

Grey relational analysis method is mainly based on grey system theory, which was introduced by Deng and used to show the correlations between the references and alternatives of a system [22]. The basic steps and application of fuzzy GRA method is described as follows.

The method starts with generating the decision matrix, which shows the evaluation of the suppliers according to decision maker. The linguistic scale, which is used in this part, is shown in Table 5.

Table 5. Linguistic scale [23]

Linguistic variable (alternative ratings)	Triangular fuzzy number
Poor - P	(0,0,6)
Fair - F	(4,7,10)
Good - G	(8,11,14)
Very good - VG	(12,15,18)
Excellent - E	(16,20,20)

After selecting the scale, the decision matrix is established according to the expert's remarks as shown in Table 6.

Table 6. Supplier ratings according to decision maker

	S_1	S_2	S_3	S_4
C_1	*G*	*G*	*G*	*G*
C_2	*F*	*V*	*G*	*G*
C_3	*G*	*E*	*V*	*G*
C_4	*E*	*V*	*G*	*G*
C_5	*F*	*V*	*G*	*G*
C_6	*G*	*V*	*V*	*V*
C_7	*F*	*E*	*V*	*G*
C_8	*G*	*V*	*V*	*G*
C_9	*F*	*V*	*V*	*V*
C_{10}	*F*	*G*	*G*	*G*
C_{11}	*P*	*V*	*G*	*G*
C_{12}	*P*	*V*	*E*	*V*
C_{13}	*F*	*V*	*V*	*G*

The normalized decision matrix [24] is obtained and shown partly in Eq. (4).

$$X^{*}=\begin{pmatrix} (0.571429, 0.785714, 1) & (0.222222, 0.388889, 0.555556) & \cdots & (0.222222, 0.388889, 0.555556) \\ (0.571429, 0.785714, 1) & (0.666667, 0.833333, 1) & \cdots & (0.666667, 0.833333, 1) \\ (0.571429, 0.785714, 1) & (0.444444, 0.611111, 0.777778) & \cdots & (0.666667, 0.833333, 1) \\ (0.571429, 0.785714, 1) & (0.444444, 0.611111, 0.777778) & \cdots & (0.444444, 0.611111, 0.777778) \end{pmatrix} \quad (4)$$

The reference series [24] are obtained and shown partly in Eq. (5).

$$\tilde{R}_0=\left[(0.571429, 0.785714, 1), (0.666667, 0.833333, 1), \cdots, (0.666667, 0.833333, 1)\right] \quad (5)$$

The distance between the reference value and each comparison value is computed [24]. The grey relational coefficient is calculated [24] via the distance matrix and grey relational coefficient matrix shown partly in Eq. (6).

$$\gamma_{0i}=\begin{pmatrix} 1 & 0.486638 & 0.520338 & 1 & 0.486638 & \cdots & 0.486638 \\ 1 & 1 & 1 & 0.685101 & 1 & \cdots & 1 \\ 1 & 0.654682 & 0.685101 & 0.520338 & 0.654682 & \cdots & 1 \\ 1 & 0.654682 & 0.520338 & 0.520338 & 0.654682 & \cdots & 0.654682 \end{pmatrix} \quad (6)$$

In the last step of fuzzy GRA, the elements of grey relational coefficient matrix are multiplied by the weights of the criteria, which is obtained from DEMATEL method. The grey relational grades, which shows the importance values of the suppliers are shown in Table 7.

Table 7. The grey relational grades of suppliers

Suppliers	Grey relational grade	Normalized values
S_1	0.586	0.190
S_2	0.945	0.307
S_3	0.827	0.268
S_4	0.724	0.235
Sum	3.082	1.000

4.3. Fuzzy Linear Programming Implementation

Each element of classical linear mathematical models has certain values and these models consist of parameters, decision variables, objective function and constraints. Fuzzy linear programming mathematical models consist of the same components but they have fuzziness and vagueness in it. As a result, there are different ways to solve the models [25]. In our study, there is vagueness in capacities, error rates and demands, which are stated in the right hand side values of constraints. Therefore, the most suitable fuzzy linear model for our problem is the approach, which was introduced by Verdegay [26]. This method is a non-symmetric model and needs to conversion to parametric programming decision model [27].

1) ***Index:***
   i : Supplier
   j : Product
2) ***Decision Variable:***
   A_{ij}: Amount of product j provided by supplier i

3) Parameters:

N : Number of suppliers
M : Number of products
w_i : The grey relational grade of supplier i
D_j : The demand of product j
C_i : The capacity of supplier i
q_i : The error rate of supplier i
Q_j : The desired error rate for product j

4) Objective Function:

The objective function of the model aims to maximize the value of purchasing (TVP) and shown by Eq. (7).

$$Max\ Z = \sum_{i=1}^{N}\sum_{j=1}^{M}(A_{ij} \times w_i) \quad (7)$$

5) Constraints:

Eq. (8) illustrates the demand of each product is satisfied. Eq. (9) shows the equality of the sum of products provided by supplier and the capacity of related supplier. Eq. (10) guarantees to maintain supplier's error rate below than desired error rate for the product. Eq. (11) shows that the decision variables are positive integers.

$$\sum_{i=1}^{N} A_{ij} \cong D_j \quad \forall j \in M \quad (8)$$

$$\sum_{j=1}^{M} A_{ij} \tilde{\leq} C_i \quad \forall i \in N \quad (9)$$

$$\sum_{i=1}^{N}(q_i \times A_{ij}) \tilde{\leq} (Q_j \times D_j) \quad \forall j \in M \quad (10)$$

$$A_{ij} \geq 0 \quad (11)$$

The related data to solve the sustainable supplier selection problem is given in Table 8 and Table 9.

Table 8. Supplier data

N	*1*	*2*	*3*	*4*
w_i	*0.190*	*0.307*	*0.268*	*0.235*
$C_i (m^2)$	*400*	*500*	*200*	*450*
$q_i (\%)$	*12*	*6*	*8*	*9*

Table 9. Product data

M	*1*	*2*	*3*
$D_j (m^2)$	*300*	*400*	*600*
$Q_j (\%)$	*10*	*8*	*9*

After the constructing the model, tolerances for demand, capacity and error rate were determined via decision maker's remarks. The tolerances were assumed to be 100 units, 100 units and 0.5, respectively. Ten membership functions for the right hand side values are obtained from the tolerances. The first membership function is shown in Eq. (12) as an example.

$$\mu_1(x) = \begin{cases} 1 & A_{11}+A_{21}+A_{31}+A_{41} < 300, \\ 1-\dfrac{(A_{11}+A_{21}+A_{31}+A_{41})-300}{100}, & 300 \leq A_{11}+A_{21}+A_{31}+A_{41} \leq 400, \\ 0 & A_{11}+A_{21}+A_{31}+A_{41} > 400, \end{cases} \quad (12)$$

λ cuts are determined for the right hand side values. Then mathematical model is converted to parametric linear model via $\theta=(1-\lambda)$ transformation. The final mathematical model is shown in Eq. (13).

$$\begin{aligned} & Max\ Z = \sum_{i=1}^{N}\sum_{j=1}^{M}(A_{ij} \times w_i) \\ & A_{11}+A_{21}+A_{31}+A_{41} = 300+100\theta \\ & A_{12}+A_{22}+A_{32}+A_{42} = 400+100\theta \\ & A_{13}+A_{23}+A_{33}+A_{43} = 600+100\theta \\ & A_{11}+A_{12}+A_{13} \leq 400+100\theta \\ & A_{21}+A_{22}+A_{23} \leq 500+100\theta \\ & A_{31}+A_{32}+A_{33} \leq 200+100\theta \\ & A_{41}+A_{42}+A_{43} \leq 450+100\theta \\ & 0.12A_{11}+0.06A_{21}+0.08A_{31}+0.09A_{41} \leq 30+300\times 0.05\theta \\ & 0.12A_{12}+0.06A_{22}+0.08A_{32}+0.09A_{42} \leq 32+400\times 0.05\theta \\ & 0.12A_{13}+0.06A_{23}+0.08A_{33}+0.09A_{43} \leq 54+600\times 0.05\theta \end{aligned} \quad (13)$$

Parametric linear programming model was solved in LINDO 6.1 For different θ values, the order quantities are obtained and shown in Table 8.

The decision maker has different alternatives for the selection of suppliers within tolerances. According to different levels of demand, capacity and error rate, the quantities of products to be procured by the suppliers can be determined from Table 10.

5. Conclusions

In this paper, an integrated approach is proposed for sustainable supplier selection problem using fuzzy DEMATEL, fuzzy GRA and fuzzy linear programming. The weights of the criteria based on sustainability dimensions are determined via DEMATEL. The importance values of suppliers are calculated using GRA. These outputs are used as inputs for fuzzy linear programming model and the quantities of products to be provided by the suppliers were obtained. For future research, a multi-objective mathematical model considering the minimization of total costs can be built to obtain a more realistic outcome. Another interesting research direction can be to add more realistic constrains such as carbon gas emissions into the models.

Table 10. The quantities for different θ values

θ	**1.0**	**0.9**	**0.7**	**0.5**	**0.3**	**0.1**	**0.0**
A_{11}	150	150	150	150	150	150	150
A_{12}	-	-	-	-	-	-	-
A_{13}	-	-	-	-	-	-	-
A_{21}	-	-	-	-	-	-	-
A_{22}	450	440	420	200	380	290	350
A_{23}	150	150	150	350	150	220	150
A_{31}	250	240	220	-	180	90	150
A_{32}	50	50	50	250	50	120	50
A_{33}	-	-	-	-	-	-	-
A_{41}	-	-	-	200	-	70	-
A_{42}	-	-	-	-	-	-	-
A_{43}	550	540	520	300	480	390	450
Z	422.35	414.25	398.05	381.85	365.65	349.45	341.35

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