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Sustainable Supplier Selection and Order Allocation Problem Using FMEA and Fuzzy MOORA

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ABSTRACT

Recently, sustainable supply chain management (SSCM) has become one of the important subjects in the industry and academia. Supplier selection, as a strategic decision, plays a significant role in SSCM. Researchers use different multi-criteria decision making (MCDM) methods to evaluate and select sustainable suppliers. In the previous studies, evaluation is solely based on the desirable features of suppliers and their risks are neglected. Therefore, current research uses failure mode and effects analysis (FMEA) as a risk analysis technique to consider supplier's risk in combination with the MCDM method. Practically, this study operated in two main stages. In the first stage, the score of the suppliers obtains by integration Fuzzy MOORA and FMEA. In the second stage, the output of the previous stage used as input parameters in developed mix-integer linear programming to select suppliers and order optimum quantity. Finally, to demonstrate the effectiveness of the proposed approach, a case study in a chemical industry and sensitivity analysis is presented.

1. Introduction

Supplier selection is an important task to have a sustainable supply chain [1]. Supplier selection is a process of ordering optimum quantities from the best supplier(s) with the right price and quality at the right time [2]. It is important because it has a huge effect on the strategic and operational performance of the organization. Furthermore, selecting the right suppliers reduces production and inventory costs, improves quality, flexibility and customer satisfaction [3]. These days, because of laws and regulations for gaining an advantage, many firms incorporate environmental criteria into the economic calculations. In addition, there is another concept known as a sustainable supply chain that considers economic, environmental and social criteria, simultaneously. Table 1 shows the definitions of sustainability in different sources in the literature.
To rank and select best suppliers, researchers considered the sustainability of supplier as a desirable feature and used multi-criteria decision-

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making methods (MCDM) such as analytical hierarchy process (AHP), analytic network process (ANP), TOPSIS, fuzzy AHP, etc.

Tab. 1. Sustainability definition

Researcher	Definition
[4]	Integration of economic, social and environmental problems.
[5]	Satisfy the needs of the current generation without limiting next generation's.

However, there is an important point that researchers have neglected: in the real world, there are suppliers that have acceptable performance in sustainable factors, but they are faced with different risk. For instance, consider a supplier which offers a low purchase cost most of the time, but in of instability, its cost raises 50 percent over normal cost. MCDM methods in the literature, consider the overall performance of suppliers and neglecting the risk of raising prices. To have a wide view on the supplier selection problem, it is essential to consider risks in the MCDM methods. One of the well-known techniques for risk analysis is failure mode and effect analysis (FMEA). Failure mode and effect analysis was developed in the 1950s for military goals. Also, in the industry, it used as a part of six sigma methodology [6] and [7].

2. Methods

The procedure for ranking and evaluating supplier in the current paper is composed of two main steps: in the first step, score and rank of each supplier are obtained by fuzzy multi-objective optimization on the basis of ratio analysis (MOORA) as an MCDM method. After that, FMEA technique was used to assess the amount of risk for suppliers. In the second step, order allocation is done by integration first step results and using the developed mathematical model.

2-1. Fuzzy multi-objective optimization on the basis of ratio analysis (Fuzzy MOORA)

The main reasons for application of fuzzy MOORA instead of applying other well-known MCDM methods are:

1. MOORA is one of the recent MCDM methods proposed for overcoming the weak aspects of the older methods.
2. MOORA is easy to apply and has a stable nature as the literature indicates.

The steps of fuzzy MOORA with ration approach can be enumerated as follows [8]:

Step 1: By using a triangular fuzzy number a decision matrix with m alternatives and n criteria are formed as:

$$\tilde{X} = \begin{bmatrix} \left[x_{11}^{l}, x_{11}^{m}, x_{11}^{u}\right] & \left[x_{12}^{l}, x_{12}^{m}, x_{12}^{u}\right] & \cdots & \left[x_{1n}^{l}, x_{1n}^{m}, x_{1n}^{u}\right] \\ \cdots & \cdots & \cdots & \cdots \\ \left[x_{m1}^{l}, x_{m1}^{m}, x_{m1}^{u}\right] & \left[x_{m2}^{l}, x_{m2}^{m}, x_{m2}^{u}\right] & \cdots & \left[x_{mn}^{l}, x_{mn}^{m}, x_{mn}^{u}\right] \end{bmatrix}$$

Step 2: The decision matrix in the previous step is normalized. This process can be done using the method introduced by [9] as follows:

$$x_{ij}^{l*} = \frac{x_{ij}^{l}}{\sqrt{\sum_{i=1}^{m}\left[\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{m}\right)^2 + \left(x_{ij}^{u}\right)^2\right]}} \tag{1}$$

$$x_{ij}^{m*} = \frac{x_{ij}^{m}}{\sqrt{\sum_{i=1}^{m}\left[\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{m}\right)^2 + \left(x_{ij}^{u}\right)^2\right]}} \tag{2}$$

$$x_{ij}^{u*} = \frac{x_{ij}^{u}}{\sqrt{\sum_{i=1}^{m}\left[\left(x_{ij}^{l}\right)^2 + \left(x_{ij}^{m}\right)^2 + \left(x_{ij}^{u}\right)^2\right]}} \tag{3}$$

Step 3: Weighted normalized decision matrix is formed by multiplying criteria weights w_j by the normalized decision matrix.

$$V_{ij}^{u} = w_j x_{ij}^{u*}$$

$$V_{ij}^{m} = w_j x_{ij}^{m*}$$

$$V_{ij}^{l} = w_j x_{ij}^{l*}$$

Step 4: This step performance of normalized value should be calculated by the following formula:

$$\bar{y}_i = \tilde{V}_{ij}^{+} - \tilde{V}_{ij}^{-} \tag{4}$$

in which $\tilde{V}_{ij}^{+}$ is performance value of positive criteria and $\tilde{V}_{ij}^{-}$ is performance value of negative criteria.

Step 5: To change the normalized fuzzy performance value as a non-fuzzy value, this study uses the following equation called the best non-fuzzy performance (BPN):

$$BPN_i\left(y_i\right) = \frac{\left(y_i^{u} - y_i^{l}\right) + \left(y_i^{m} - y_i^{l}\right)}{3} + y_i^{l} \tag{5}$$

where $\tilde{y}_i = \left(y_i^{l}, y_i^{m}, y_i^{u}\right)$

After implementation of the above BPN formula, the supplier can be ranked by sorting from the largest value to the smallest. The biggest one is the best.

2-2. Failure mode and effects analysis (FMEA)

Determining the risk criteria is the first step for evaluation supplier's risk. By using company's historical data and review previous literature, expert team can select important risk criteria. For the implementation of FMEA, we should examine three aspects of risks, namely: severity, occurrence and detection then design FMEA scheme for every criterion. Following Carlson [10], this paper uses 1-10 point scale to design the scheme. Table 2 is a general form of a scheme that applies in various cases [7].

Tab. 2. General evaluation scheme

Rank	Severity	Occurrence	Detection
9-10	Failure to meet safety or regulatory requirements	Very high and inevitable	No detection chance
7-8	Loss or degradation of primary function	High and uncertain	Probably detected by offline Testing
5-6	Loss or degradation of secondary function	Moderate	Probably detected by online planned testing
2-4	Annoying effect	Low	Probably detected by online continuous testing
1	No discernible effect	Very low	Highly visible

After designing the scheme, the decision makers and the expert team select the ranks of criteria in severity, occurrence and detection.

Risk priority number (*RPN*) concept is a method that changes FMEA scheme to numbers. Assume *S, O* and *D* are ranking number for severity, occurrence and detection, respectively. One of the simplest and oldest formula for *RPN* is multiplying *S, O* and *D*. However, this formula has a lot of weaknesses. Li and Zeng [7] enhanced *RPN* formula as follows:

They defined *L* as a risk number that is multiplied *S* and *O* which *L=S*O*. Also, they defined risk percentage with the following formula:

$$RPN = \frac{(L-1)*100}{99} \tag{6}$$

In equation (6), detection has no role in the formula. Therefore, they defined $ep = -0.1 * d + 1.55$ and introduced final *RPN* as:

$$RPN = \left(\frac{(L-1)}{99}\right)^{ep} *100 \tag{7}$$

Justification of *ep* formula is that because detection scale is between 1 and 10. So, when detection is in the middle or 5.5 the influence of detection of the total risk should be none. So, when detection is 5.5, *ep* is equal to 1 and has no effects on *RPN*. Finally, risk discount that is useful for assessing supplier can be obtained by multiplying the risk from FMEA and the score from MOORA by the following formula:

Risk discount= Fuzzy MOORA* (1-Risk) (8)

The fuzzy MOORA result reveals the desirable aspect and the risk shows the negative. So, direct multiplication is not reasonable for this reason Equation (8) is used to integrate the result of fuzzy MOORA and FMEA.

2-3. Mathematical model

After applying of Fuzzy MOORA and FMEA, to obtain a widespread score of the suppliers, the MILP model developed to select suppliers and assign an optimum quantity of each item to them. So, it is clear that by using the proposed approach in this study, order allocation is done on the side of ranking suppliers. The objective of the model is to maximize the total suppliers score. The indices, decision variables, parameters, objective function and constraints are as follows:

Index

$I=1,2,\ldots,i$	Index of the requirement items
$J=1,2,\ldots j$	Index of the suppliers

Decision variable

X_{ij}	Amount of item *i* purchase from supplier *j*
Z_j	If supplier *j* select 1, otherwise 0

Parameter

SC_{ij}	Score of the supplier *j* for item *i* (that

	obtain according to the sections 2.1 and 2.2)
$SMAX_{ij}$	Maximum capacity of supplier j to supply item *i*
D_i	Demand for item *i*
N	Maximum number of supplier can be selected
M	A positive big number

$$MAX = \sum_i \sum_j SC_{ij} X_{ij}$$

$$X_{ij} \le SMAX_{ij} \qquad \forall i, j \qquad (9)$$

$$\sum_j X_j = D_i \qquad \forall i \qquad (10)$$

$$M.Z_j \ge \sum_i X_{ij} \qquad \forall j \qquad (11)$$

$$\sum_j Z_j \le N \qquad (12)$$

$$X_{ij} \in Integer^+, Z_j \in \{0,1\} \qquad (13)$$

The objective function is to maximize the total supplier score. Constraint (9) guarantees that amount item *i* assign to supplier *j* not exceed the maximum capacity of the supplier *j*. Based on constraint (10), all necessary items should be fulfilled from suppliers. Constraint (11) is a counter for a number of suppliers means variable Z_i will be 1 if supplier 1 select otherwise 0. The main usage of this constraint is in inequality (12). Because selecting each supplier cause fix cost like contracts. Manager express that number of the different supplier should not exceed *N*. So, constraint (12) guarantees that number of different suppliers do not exceed *N*. Constraint (13) is binary and non-negative integer constraint.

3. Case Study

The applicability of the proposed model is discussed through a case study in Tehran, Iran. The company produces different types of paints such as plastic paint, bright oil paint, swimming pool paint, spray paint, etc. Currently, sourcing strategy is based on managerial judgment and purchase history that is not scientific and sustainable. There are different types of items required for production such as Resin, Titanium, Calcium Carbonate, and Zinc Oxide. For brief, the calculation of Resin is demonstrated and final results are given for the rest of the items. Therefore, we should examine four suppliers that can supply Resin. In order to save business privacy of manufacturer and suppliers, this paper uses symbol names such as S1, S2, etc. Instead of a supplier's name. It should be noticed that each supplier cannot produce all items, So, Table 3 illustrates the ability of suppliers to produce items.

Tab. 3. Ability of the suppliers to provide items

	S1	S2	S3	S4	S5	S6	S7	S8	S9
Resin	✓		✓	✓					✓
Titanium		✓	✓		✓				
Calcium Carbonate						✓	✓		
Zinc Oxide							✓	✓	✓

Determination of important criteria according to the case study is the first step in selecting sustainable suppliers. Therefore, a meeting was held with the attendance of the experts in the company and the result is as follows:
Sustainability has three main aspects (economic, environmental and social) that have been separated for better expression.

Economic

- Cost: Supply requirement of raw material causes different costs such as purchasing cost, holding cost and ordering cost.
- Quality: This criterion shows a supplier's ability to control service and product quality.
- Delivery: This criterion is to assess delivery agility of suppliers.

Environmental

- Environmental management system (EMS): Certifications such as ISO 14000.
- Chemical leakage: Since most of the raw materials required for production are chemicals, the risk of chemical leakage is important to consider.
- Pollution: Chemical waste causing further pollution of the environment.

Social

- Worker dismissal: Shows the number of fired workers.
- Worker safety: Criterion for analysis worker injuries.
- Training, education and community development: Effective factors in this criterion can be the number of created jobs, average hours of training per year per employee for manager and personnel [11].
- The interests and rights of employee: The real implementation of worker's interests and rights.

3-1. Application of fuzzy MOORA

According to expert's opinions, effective criteria for evaluating supplier by the fuzzy MOORA method are: cost, quality, delivery, EMS, pollution, worker safety and the interests and rights of employees. After criteria selection, by using questionnaires, the expert judgments are collected. In the next step, expert's judgment is converted to fuzzy numbers using linguistic scale proposed by Awasthi, Chauhan and Goyal [12].

Tab. 4. Linguistic terms for supplier ratings

Linguistic term	Membership function
Very poor (VP)	(1,1,3)
Poor (P)	(1,3,5)
Fair (F)	(3,5,7)
Good (G)	(5,7,9)
Very good (VG)	(7,9,9)

To avoid complicated calculation, decision matrix prepared just for Resin according to linguistic terms in Table 4 and the results show in Table 5. According to step 2 in the fuzzy MOORA method, decision matrix in Table 5 should be normalized by using Equations (1)-(3). So, Table 6 is a normalized decision matrix for Resin. Next step, normalize matrix should multiply in weight of the criteria. Criteria weights according to Table 6 are 0.16, 0.2, 0.13, 0.12, 0.14, 0.13 and 0.12 respectively. For example, weight for cost is 0.16 and quality is 0.2. By multiplication, weighted normalize decision matrix obtains as Table 7.

According to the nature of the criteria, the amount of $\overline{y}_i$ is calculated by using Equation (4) and the result is illustrated in the first three columns of Table 8. But, they are a fuzzy number that is not compatible to use for comparison and ranking. So, Equation (5) is used to reform fuzzy as a single number and the result is shown in the fourth column of Table 8. For the rest of suppliers and items similar calculation was done and results summarize are shown in Table 9.

Tab. 5. Decision matrix for Resin

	Economic			Environmental		Social	
	Cost	Quality	Delivery	EMS	Pollution	Worker safety	Interests and rights of the employee
S1	(1,3,5)	(5,7,9)	(3,5,7)	(1,3,5)	(5,7,9)	(3,5,7)	(1,3,5)
S3	(3,5,7)	(5,7,9)	(1,3,5)	(5,7,9)	(1,3,5)	(1,3,5)	(7,9,9)
S4	(5,7,9)	(5,7,9)	(3,5,7)	(5,7,9)	(7,9,9)	(7,9,9)	(7,9,9)
S9	(3,5,7)	(3,5,7)	(5,7,9)	(1,3,5)	(3,5,7)	(3,5,7)	(5,7,9)

Tab. 6. Normalize decision matrix for Resin

	Cost	Quality	Delivery	EMS	Pollution	Worker safety	Interests and rights of the employee
S1	(0.047,0.140,0.233)	(0. 175,0.246,0. 316)	(0.120,0.199,0.279)	(0.039,0.117,0.196)	(0.192,0.269,0.346)	(0.110,0.184,0.257)	(0.031,0.094, 0.157)
S3	(0.140,0.233,0.326)	(0. 175,0.246,0. 316)	(0.040,0.120,0.199)	(0.196,0.274,0.352)	(0.038,0.038,0.115)	(0.037,0.110,0.184)	(0.220,0.283, 0.283)
S4	(0.233,0.326,0.419)	(0. 175,0.246,0. 316)	(0.120,0.199,0.279)	(0.196,0.274,0.352)	(0.115,0.192,0.269)	(0.257,0.331,0.331)	(0.220,0.283, 0.283)
S9	(0.140,0.233,0.326)	(0.105,0.175,0.246)	(0.199,0.279,0.359)	(0.039,0.117,0.196)	(0.192,0.269,0.346)	(0.110,0.184,0.257)	(0.157,0.220, 0.283)

Tab. 7. Weighted normalize decision matrix for Resin

	Cost	Quality	Delivery	EMS	Pollution	Worker safety	Interests and rights of the employee
S1	(0.007,0.021,0.034)	(0.035,0.049,0.063)	(0.015,0.025,0.035)	(0.047,0.014,0.023)	(0.028,0.040,0.051)	(0.016,0.027,0.038)	(0.031,0.009,0.015)
S3	(0.021,0.034,0.048)	(0.035,0.049,0.063)	(0.005,0.015,0.025)	(0.023,0.039,0.042)	(0.005,0.005,0.017)	(0.005,0.016,0.027)	(0.022,0.028,0.028)
S4	(0.034,0.048,0.062)	(0.035,0.049,0.063)	(0.015,0.025,0.035)	(0.023,0.039,0.042)	(0.017,0.028,0.040)	(0.038,0.049,0.049)	(0.022,0.028,0.028)
S9	(0. 021,0.034,0.048)	(0.021,0.035,0.049)	(0.025,0.035,0.045)	(0.004,0.014,0.023)	(0.028,0.040,0.051)	(0.016,0.027,0.038)	(0.015,0.022,0.028)

Tab. 8. Result of fuzzy MOORA to supply Resin

	y_i^l	y_i^m	y_i^u	Score	Rank
S1	0.1108	0.1874	0.2640	0.1874	3
S3	0.1180	0.1830	0.2533	0.1848	4
S4	0.1869	0.2635	0.3228	0.2577	1
S9	0.1337	0.2103	0.2869	0.2103	2

Tab. 9. Result of the fuzzy MOORA for all suppliers with the respect to each item

Item	supplier	y_i^l	y_i^m	y_i^u	Score	Rank
Resin	S1	0.1108	0.1874	0.2640	0.1874	3
	S3	0.1180	0.1830	0.2533	0.1848	4
	S4	0.1869	0.2635	0.3228	0.2577	1
	S9	0.1337	0.2103	0.2869	0.2103	2
Calcium Carbonate	S2	0.1337	0.1964	0.2730	0. 2194	1
	S3	0.0581	0.1066	0.1973	0.1207	3
	S5	0.1485	0.2251	0.2844	0.2010	2
Titanium	S6	0.0702	0.1329	0.2095	0.1375	2
	S7	0.1300	0.2003	0.2769	0.2024	1
Zinc Oxide	S7	0.1314	0.2080	0.2846	0.2080	1
	S8	0.0803	0.1459	0.2225	0.1496	3
	S9	0.1258	0.1884	0.2395	0.1846	2

3-2. Application of the FMEA

According to expert's opinion, effective risk criteria for current case study are cost, quality, delivery, chemical leakage, and worker safety and worker dismissal. To evaluate the total risk, an FMEA scheme considering severity, occurrence and detection for every criterion is designed. FMEA scheme for cost is given in Table 10. Furthermore, scheme for other criteria is provided in the appendix. After scheme preparation, the computing part of FMEA must be implemented. For the cost, decision makers expressed that supplier S1 has a price which is 4% more than market price (severity); this happens about 8% of the time (occurrence) and the ability to predict the exact amount fluctuates from one period to another (detection).

Tab. 10. FMEA scheme for cost

Rank	Severity	Occurrence	Detection
10	More than 11 % above market price	About 15% happen per period	No chance to detect
8-9	8 % more than market price	More than 10% per period	The ability to predict the occurrence a week ago
6-7	5 % more than market price	About 8% happen during time horizon	The ability to predict the exact amount fluctuates from a week ago
4-5	4 % more than market price	About 6% happen during time horizon	The ability to predict the occurrence of fluctuations in a prior period
2-3	2 % more than market price	About 4% happen during time horizon	The ability to predict the exact amount fluctuates from one period
1	Equal to market price	Always equal to market price	Quite predictable before scheduling

Tab. 11. Expert's judgment for risk criteria of Resin

	Cost			Quality			Delivery			Chemical leakage			Worker safety			Worker dismissal		
	S*	O*	D*	S	O	D	S	O	D	S	O	D	S	O	D	S	O	D
S1	4	6	2	3	3	6	2	5	6	6	3	6	2	1	5	3	1	2
S3	3	3	3	5	6	6	5	3	4	6	5	6	2	3	1	2	1	1
S4	1	2	5	5	5	8	5	4	2	2	6	4	2	2	4	1	5	1
S9	3	4	4	1	3	3	2	3	3	1	1	5	1	2	3	2	3	1

S: severity, O: occurrence, D: detection

Thus, Table 10 shows that cost ranks for S1-Resin are 4, 6 and 2 in severity, occurrence and detection, respectively. Also, Table 11 shows expert's judgment for rest of risk criteria of Resin. From the formulations in section 2.2, L = 24 and ep = 1.35, so as a result, the risk of S1-Resin for the cost is equal to R = 0.139. Similarly, the amounts of the risk for the rest of the criteria are obtained and summarize in Table 12.

Tab. 12. Unweighted amount of risk for Resin

	Cost	Quality	Delivery	Chemical leakage	Worker safety	Worker dismissal
	Risk					
S1	0.1394	0.0916	0.1025	0.1875	0.008	0.0052
S3	0.431	0.3115	0.1055	0.3115	0.0132	0.0013
S4	0.080	0.3455	0.1077	0.0799	0.0179	0.0095
S9	0.799	0.0076	0.0239	0.00	0.0032	0.0132

Next step, because different criteria do not have the same importance, the amount of unweight risk should be multiplied in criteria's weight to have realistic output. Table 13 shows the weight of criteria (second row), the weighted amount of risk for Resin's suppliers and total risks. The total risk of suppliers (last column) is equal to the summation of risk in every criterion, for instance, the total risk of S1 in Resin obtain as follows:

S1-Resin risk= cost risk+ quality risk+… worker dismissal risk=0.0279+0.0165+…+0.0007=0.097.

Tab. 13. Weighted amount of risk for Resin

	Cost	Quality	Delivery	Chemical leakage	Worker safety	Worker dismissal	Total risk
Weight	0.2	0.18	0.15	0.19	0.15	0.13	
S1	0.0279	0.0165	0.0154	0.0356	0.0012	0.0007	0.097
S3	0.0086	0.0561	0.0158	0.0592	0.002	0.0002	0.142
S4	0.0016	0.0622	0.0162	0.0152	0.0027	0.0012	0.099
S9	0.0160	0.0014	0.0036	0.00	0.0005	0.0017	0.023

Finally, Table 14 shows the result of FMEA and the risk of the supplier to supply each item. After all, the output from fuzzy MOORA should be multiplied in (1-FMEA) to have a widespread judgment about suppliers. Table 15 shows the final result and final rank of every supplier.

Solving developed mathematical model is the last phase of the proposed approach. Input parameters for the model are SC_{ij} which is shown in Table 15, the maximum capacity of suppliers represented in Table 16 and demand for items in the planning horizon prepared in Table 17. It should be noticed that the maximum available number of suppliers, according to manager expression is five (N=5).

Tab. 14. Result of FMEA for all suppliers with the respect to each item

	Resin				Calcium Carbonate			Titanium		Zinc Oxide		
	S1	S3	S4	S9	S2	S3	S5	S6	S7	S7	S8	S9
FMEA	0.097	0.142	0.099	0.023	0.077	0.087	0.229	0.141	0.145	0.256	0.036	0.059
(1-FMEA)	0.903	0.858	0.901	0.977	0.923	0.913	0.771	0.859	0.855	0.744	0.964	0.941
Ranking in risk	2	4	3	1	1	2	3	1	2	3	1	2

Tab. 15. Final result of suppliers with the respect to each item

	Resin				Calcium Carbonae			Titanium		Zinc Oxide		
	S1	S3	S4	S9	S2	S3	S5	S6	S7	S7	S8	S9
FMEA & fuzzy MOORA	0.169	0.159	0.232	0.2	0.186	0.110	0.169	0.118	0.173	0.155	0.144	0.174
Final rank	3	4	1	2	1	3	2	2	1	2	3	1

Tab. 16. Maximum capacity of suppliers with respect to each item

	S1-Resin	S3-Resin	S4-Resin	S9-Resin	S2-Cal-Carb	S3-Cal-Carb	S5-Cal-Carb	S6-Titanium	S7-Titanium	S7-Zinc Oxide	S8-Zinc Oxide	S9-Zinc Oxide
capacity	12000	6500	8000	3000	500	1000	1000	2000	2000	3500	4200	2000

Tab. 17. Demand of items

	Resin	Titanium	Calcium Carbonate	Zinc Oxide
Demand (D_i)	6000	1200	1500	2300

Tab. 18. Order allocation

	Supplier								
	S1	S2	S3	S4	S5	S6	S7	S8	S9
Resin	0	0	0	6000	0	0	0	0	0
Titanium	0	500	0	0	700	0	0	0	0
Calcium Carbonate	0	0	0	0	0	0	1500	0	0
Zinc Oxide	0	0	0	0	0	0	300	0	2000

This study uses LINGO 16 for the solving the mathematical model. According to the case, decision variables obtain as Table 17. For instance, the company needs 1300 unit of Titanium, and 500 unit Titanium should be purchased from supplier2 (S2) and 700 unit from supplier5 (S5).

4. Sensitivity Analysis

In this section, two sensitivity analysis are prepared to validate the results of proposed approach and show benefits that gain by the implementation of the proposed approach. In the first analysis, the rank of the supplier is considered before and after considering risks. Also, the second analysis shows the influence of the developed method on the amount of order from each supplier.

4-1. Analysis of ranks

A sensitivity analysis is presented in Fig 1. Suppliers that can supply Zinc Oxide are S7, S8 and S9. As illustrated in Fig 1, S7 in Zinc Oxide has rank 1 in fuzzy MOORA. So, if we select supplier just base on MCDM method, S7-Zinc Oxide will be chosen at the first. But, after risk consideration and implementation of FMEA, it's clear that S7-Zinc Oxide has the worst performance in risk and its rank is 3. After integration FMEA and fuzzy MOORA, the rank of S7-Zinc Oxide change as a 2 that is reasonable rank because it considers the position of the supplier in fuzzy MOORA and FMEA. It should be noted in most of the time, fuzzy MOORA and integration rank are close to each other, unless, supplier are faced with huge risk in reality.

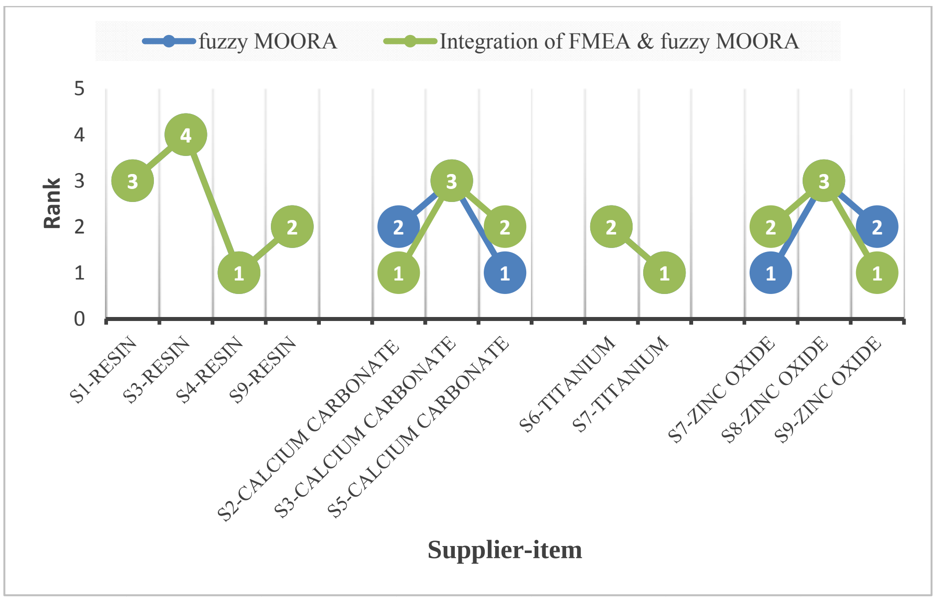

Fig. 1. Ranks of suppliers according to fuzzy MOORA, FMEA and integration of them

4-2. Order allocation analysis

To demonstrate how much proposed approach enhances order allocation, the proposed mathematical model solves in three different times: At the first time, we use the results of fuzzy MOORA as SC_{ij} parameter, the second time, FMEA results use as SC_{ij} and the last time, integration of FMEA and fuzzy MOORA use as an input parameter for the model. The amount of order allocation obtain from three above situations, prepare in Table 18. Furthermore, for a better comparison, some results are illustrated in Fig 2. It is clear that in some cases like Zinc Oxide, implement of the proposed approach have a huge effect on order allocation, because according to fuzzy MOORA all 2300 unit necessary items should be purchased from S7 and according to FMEA must be purchased from S8. But, by the implementation of the proposed method and integration fuzzy MOORA and FMEA in order to balance between risk and fuzzy MOORA, the model divides the amount of order into two parts and order 2000 units from S9 and 300 units from S7. But in some cases like S4-Resin that suppliers do not face with significant risk there is not the difference between the amount of order before and after risk consideration.

Tab. 19. Order allocation in the different situations

Item	Supplier	Fuzzy MOORA	FMEA	Fuzzy MOORA and FMEA
Resin	S1	0	3000	0
	S3	0	0	0
	S4	6000	0	6000
	S9	0	3000	0
Calcium Carbonate	S2	200	500	500
	S3	0	700	0
	S5	1000	0	700
Titanium	S6		1500	0
	S7	1500	0	1500
Zinc Oxide	S7	2300	0	300
	S8	0	2300	0
	S9	0	0	2000

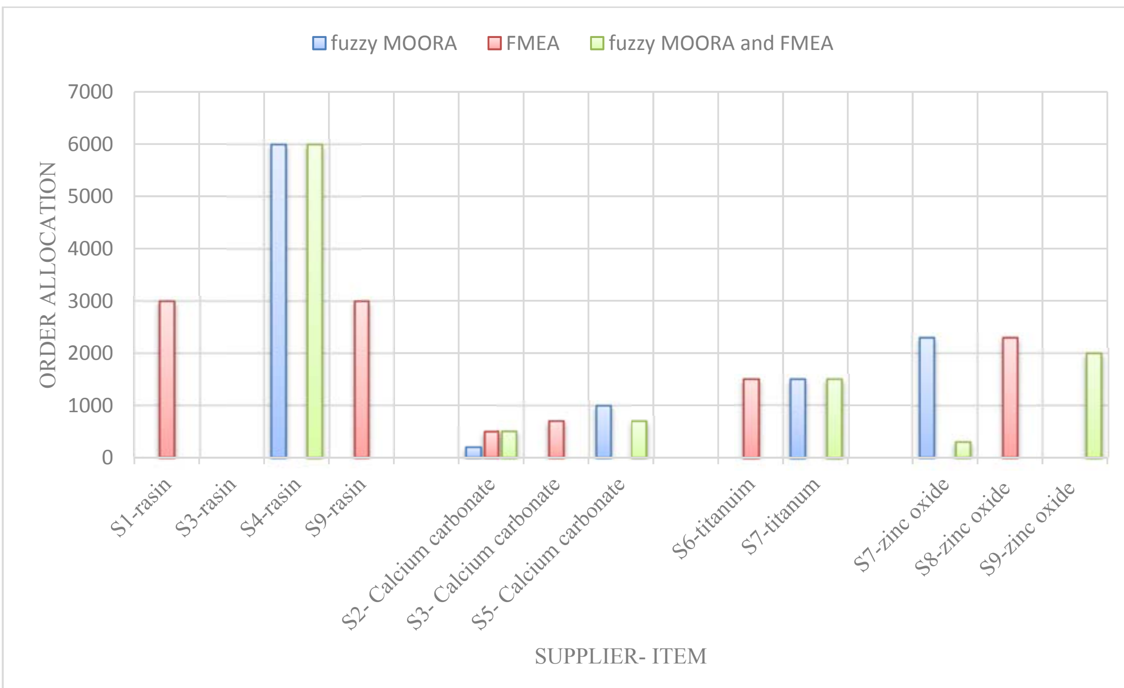

Fig. 2. Amount of order allocation in the different situations

5. Concluding Remarks

There are many research that utilized different types of MCDM methods to evaluate the sustainability of the suppliers, but there is a weakness that can be explained as follow. There are some positive aspects such as lower costs and negative aspects such as supply risks, when someone desire to evaluate the companies. A basic assumption of the MCDM techniques is considering the positive aspects of the suppliers. It mainly efforts to select suppliers with the maximum positive score. However, to have a comprehensive perspective on the supplier, it is necessary to consider the negative aspects of suppliers as well. Due to the importance of negative considerations, this study uses risk notion as a negative aspect of the suppliers.

To the best of the author's knowledge, suppliers' risks and scores are not assessed together in the previous research. Therefore, the current study is the first research that provided a relation between risk and score by using the FMEA technique and fuzzy MOORA method for selecting sustainable suppliers. This novel approach provides a wide perspective on the performance of suppliers. This study can be extended in different dimensions. To deal with the uncertainty of risk and FMEA, gray FMEA can be utilized in the evaluation process. Moreover, the effect of criteria can be evaluated and analyzed by using a regression model before implementation of an MCDM model. Finally, a mathematical model can be extended considering the discount rates.

Appendix: FMEA Evaluation schemes for the real-case application

This Appendix reports the FMEA evaluation schemes for the real-case application in view of severity (Table A1), likelihood (Table A2), and control (Table A3).

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Appendix

Tab. A1. Severity scheme

	Cost	Quality	Delivery	Chemical leakage	Worker safety	Worker dismissal
10	More than 11 % above market price	More than 6% defeat per batch	More than one week delay	Depletion all shipments	Mass disasters for the workers	More than 25% dismiss
8-9	8 % more than market price	5% defeat per batch	One week delay	Leakage half a shipment	More than 30% mutilation	20% dismiss
6-7	5 % more than market price	4% defeat per batch	Half a week delay	30% leakage occurs	More than 20% mutilation	15% dismiss
4-5	4 % more than market price	3% defeat per batch	One day delay	10% leakage occurs	Partial Mutilation	10% dismiss
2-3	2 % more than market price	1.5% defeat per batch	Half a day delay	Low leakage occurs	Partial injury	5% dismiss
1	Equal to market price	1% defeat per batch	on time	Without leakage	Without any incident	without dismiss

Tab. A2. Occurrence scheme

	Cost	Quality	Delivery	Chemical leakage	Worker safety	Worker dismissal
10	About 15% happen per period	More than 6 times per period	More than 6 times during time horizon	More than 4 times during time horizon	More than 6 times during time horizon	More than 5 times during time horizon
8-9	More than 10% per period	5 times per period	5 times during time horizon	4 times during time horizon	5 times during time horizon	4 times during time horizon
6-7	About 8% happen during time horizon	4 times per period	3 times during time horizon	3 times during time horizon	3 times during time horizon	3 times during time horizon
4-5	About 6% happen during time horizon	3 times per period	2 times during time horizon	2 times during time horizon	2 times during time horizon	2 times during time horizon
2-3	About 4% happen during time horizon	1.5 times per period	Just 1 times during time horizon	Just 1 times during time horizon	Just 1 times during time horizon	Just 1 times during time horizon
1	Always equal to market price	1 times per period	Always deliver at exactly right time	Always deliver at exactly right time	Never happens	Never happens

Tab. A3. Detection scheme

	Cost	Quality	Delivery	Chemical leakage	Worker safety	Worker dismissal
10	No chance to detect	No chance to detect	No chance to detect	No chance to detect	No chance to detect	No chance to detect
8-9	The ability to predict the occurrence a week ago	Random inspection only	Without regular production schedule	Rarely predictable	Rarely predictable	Just a month earlier predictable
6-7	The ability to predict the exact amount fluctuates from a week ago	permissive Sampling inspection	Do not share production schedule	Sometimes predictable	Sometimes predictable	Cannot be determined until the end of the last period

4-5	The ability to predict the occurrence of fluctuations in a prior period	Strict sampling inspection	Non on time access production schedule	Usually predictable	Usually predictable	After two period of planning is detectable
2-3	The ability to predict the exact amount fluctuates from one period	General inspection before loading	Share production schedule	Most of the time predictable	Most of the time predictable	After a period of planning is detectable
1	Quite predictable before scheduling	Can be detected	From prior period absolutely predictable	Quite predictable	Quite predictable	Before planning quite predictable

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