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Designing a supply chain by considering secondary risks in the case of food industry: an integrated interval type-2 fuzzy approach

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Abstract *– In this study, we combine an interval type-2 fuzzy best-worst method (IT2FBWM) with the interval VIKOR method for the first time to evaluate and prioritize sustainable suppliers in circular supply chains. To weigh the criteria, an interval type-2 best worst approach is employed, and the interval VIKOR methodology is utilized to assess the suppliers in the presence of uncertainty. Risk is presented in all supply chain activities, and its occurrence affects all dimensions of the supply chain and can cause damage to them and, therefore, must be appropriately managed. A new mixed-integer linear programming model is then formulated to identify each risk's optimal strategy or response. The multi-objective model minimizes total costs and response time and maximizes risk responses to secondary and primary risks. An improved version of augmented ε-constraint method (AUGMECON2) is also employed to produce separate Pareto-optimal solutions. Finally, the suggested strategy is applied to four main suppliers in the food company. The findings of the proposed integrated approach demonstrate the applicability and efficiency in the food industry.*

Keywords*– Supply Chain, Sustainable supplier selection, Interval type-2 fuzzy sets, Best-Worst method, Interval VIKOR, Multi-objective model.*

I. INTRODUCTION

Due to the strong competition in the market, businesses must employ several techniques to succeed. Customers' growing knowledge of environmental issues, as well as the overuse of natural resources, have encouraged businesses to consider environmental concerns when deciding on the best approach. On the other hand, eco-friendly and sustainable techniques cannot be selected in isolation and must be combined with social concerns [1].

Sustainability should take into account economic, environmental, and social considerations, according to the triple bottom line principle. Companies are under pressure to incorporate circular economy (CE) into their strategy and supply chains in the face of a rapidly changing environment. The basic idea of CE is to make maximum use of products, components, and resources in order to achieve zero-waste ideals. As a result, biological products can be safely returned to the biosphere. In addition to biological products, other items can be remanufactured, recycled, or reconditioned to reduce waste [1].

Many scholars have recently been interested in this study area. For example, Genovese et al. [2] and Nasir et al. [3] have demonstrated that incorporating CE into supply chain management offers significant long-term advantages for

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businesses.

It is anticipated that the global community will produce 1.3 billion tons of waste each year. By 2050, it is expected to rise to 2.2 billion tons, highlighting the urgent need to incorporate sustainability considerations. The circular economy (CE) is a relatively new method for reducing negative environmental effects [4]. The circular supply chain (CSC) and the sustainable supply chain vary in some ways. The first is that CSCs have restorative and regenerative cycles, allowing biological and technological elements to be securely disposed of while still gaining maximum use. The second is the concept of no waste, which is unique to the CE philosophy [1].

Product and service design [5], [6], procurement [7], [8], and logistics [9] are some of the applications of supply chain operations combining CE that have been studied in the literature. Since a supply chain begins its operations with a supplier, additional emphasis is placed on the procurement function. However, there is a lack of research on circular supplier selection (CSS). Until now, a few researchers have focused on this problem. For example, Mina et al. [10] developed a combined AHP and TOPSIS approach with a fuzzy inference system to evaluate and rank circular suppliers in a petrochemical company. Kannan [11] applied the best-worst method and interval VIKOR to evaluate the suppliers with respect to economic, social, and circular criteria in the wire-and-cable industry.

A two-stage multi-objective possibilistic integer linear programming sustainable supply chain network design model was proposed in research [12]. The green image weights of suppliers are evaluated in the first stage using BWM (Best-Worst technique) and TOPSIS. Possibilistic programming and the Epsilon (ε) constraint approach were used in this work [12].

In this study, a new selection strategy for the sustainable circular supplier problem is described, along with a new decision-making model based on interval type-2 fuzzy best-worst method (IT2FBWM) and interval VIKOR methods. Then, an application case from the food company is shown and solved using the suggested decision under uncertainty.

The rest of this paper is arranged as follows. In Section 2, we examine the research background. Section 3 presents the IT2FBWM and Interval VIKOR. In Section 4, we describe our case study and outcomes. Section 5 concludes with our findings.

II. PRELIMINARIES

A. Type-2 fuzzy set

A type-1 fuzzy variable is defined as a function from the possibility space to the set of real numbers, a type-2 fuzzy variable, known as a function from the fuzzy possibility space to the set of real numbers [13], [14]. If *(*Θ*, p, Pos)* is a fuzzy possibility space, then a type-2 fuzzy variable $\tilde{\xi}$ is explained as a map from Θ to $\Re$ such that for any $t \in \Re$, the set $\{\gamma \in \Theta \mid \tilde{\xi}(\gamma) \le t\}$ is an component of p, i.e., $\{\gamma \in \Theta \mid \tilde{\xi}(\gamma) \le t\} \in p$ [13].

Subsequently $\tilde{\mu}_{\tilde{\xi}}(x)$, called secondary possibility distribution function of $\tilde{\xi}$, is illustrated as a map $\Re \to [0,1]$ such that $\tilde{\mu}_{\tilde{\xi}}(x) = Pos\{\gamma \in \Theta \mid \tilde{\xi}(\gamma) = x\}, x \in \Re$ and $\tilde{\mu}_{\tilde{\xi}}(x,u)$, named type-2 possibility distribution function, is a map $\Re \times J_x \to [0,1]$, detailed as $\tilde{\mu}_{\tilde{\xi}}(x,u), = Pos\{\tilde{\mu}_{\tilde{\xi}}(x,u) = u\}$, $(x,u) \in \Re \times Jx$. Therefore, clearly if $\tilde{\mu}_{\tilde{\xi}}(x,u) = 1$, $\forall (x,u) \in \Re \times J_x$, then $\tilde{\xi}$ is called an interval type-2 fuzzy (IT2F) variable.

B. IT2F sets

An IT2F sets (IT2FSs) $\tilde{A}$ in the space of discourse, X can be characterized by $\left(\tilde{A}^U, \tilde{A}^L\right) = \left(\left(a_1^U, a_2^U, a_3^U, a_4^U; h_{\tilde{A}}^U\right), \left(\left(a_1^L, a_2^L, a_3^L; h_{\tilde{A}}^L\right)\right)\right)$ where both $\tilde{A}^U$ and $\tilde{A}^L$ are fuzzy variables of height $h_{\tilde{A}}^U$ and $h_{\tilde{A}}^L$ respectively. Where, $a_1^U \leq a_2^U \leq a_3^U \leq a_4^U$, $a_1^L \leq a_2^L \leq a_3^L$, $a_1^U \leq a_1^L$, $a_3^L \leq a_4^U$ and $0 \leq h_{\tilde{A}}^L \leq h_{\tilde{A}}^U \leq 1$. Figure 1 illustrates IT2FSs.

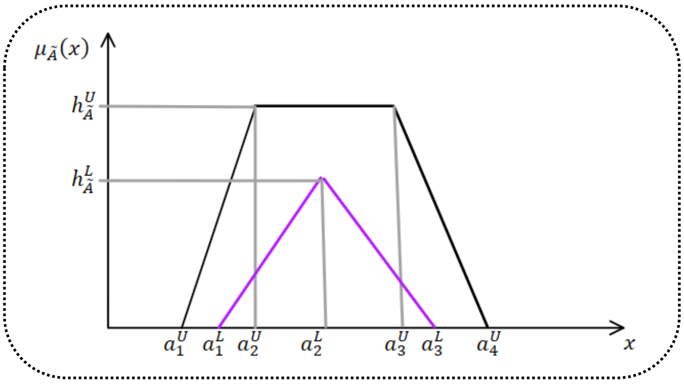


Fig 1. An IT2FSs with geometric representation [15]

C. IT2FBWM

Preference relation (PR) is a typical method for obtaining the criterion weights. Eq. (1) denotes a matrix that each element shows preference degree of criterion i over criterion j.

$$A = \begin{array}{c} \\ c_1 \\ c_2 \\ \vdots \\ c_n \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \cdots & c_n \end{array} \\ \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{1n} \end{pmatrix} \end{array} \tag{1}$$

The PR A is fully consistent if it provides $a_{ij} = a_{ik} \times a_{kj}$, $\forall i, j, k \in N$. However, inconsistencies in PRs are likely, and stating the degree of preference is the most common source of inconsistency. Rezaei [16] observed that identifying the most important and least important is rather simple and attainable when faced with a collection of criteria. After determining the best and worst criteria, the linguistic preferences may be seen in two ways:

- Best-worst linguistic reference vectors (BWLRVs);
- Secondary linguistic preference (SLP) components.

Definition 1. [16] $(a_{i1}, a_{i2}, \dots, a_{in})$ and $\left(a_{1j}, a_{2j}, \dots, a_{nj}\right)$ are known as BWLRVs such that i is the best criteria and j is the worst criteria.

Definition 2. [16] A linguistic preference element a_{ij} is defined as a SLP. For a PR with n alternatives, the total number of comparisons is n^2. Considering the reciprocity of a PR, at least $n\,(n-1)/2$ comparisons are required. However, the BWM, only $2n-3$ comparisons are desirable.

C.A. Obtain the IT2F weights of criteria

After gaining the BWLRVs, they are then changed into IT2FSs based on Table 1. The attained IT2F best-to-others and IT2F others-to-worst vectors are

$$\tilde{A}_B = \left(\tilde{A}_{B1}, \tilde{A}_{B2}, \dots, \tilde{A}_{Bn}\right), \tag{2}$$

$$\tilde{A}_w = (\tilde{A}_{1w}, \tilde{A}_{2w}, \dots, \tilde{A}_{nw}) \quad (3)$$

obviously, $\tilde{A}_{BB} = \tilde{A}_w = [(1,1,1,1),(1,1,1)]$.

Table I. FOU data for linguistic terms [15].

Words	*Normal IT2FSs*
EI	[(1.000,1.000,1.000,1.000), (1.000,1.000,1.000)]
WI	[(1.00,1.00,1.7184,2.6165), (1.000,1.0734,1.9266)]
MI	[(1.4308,2.35,2.80,3.3968), (2.5172,2.6941,3.0828)]
MP	[(2.1515,3.00,3.85,4.8107), (3.3550,3.5368,3.8278)]
SI	[(3.3101,4.25,5.05,6.0107), (4.4136,4.8900,5.0278)]
SP	[(4.6893,5.50,6.20,6.9485), (5.6379,5.8889,6.0621)]
VS	[(5.9686,6.750,7.1,8.2314), (6.7172,6.8889,7.1036)]
VVS	[(7.0136,7.65,8.00,8.7071), (7.5172,7.8125,8.0828)]
EX	[(7.0253,8.8624,9.000,9.000), (8.8684,8.9908,9.000)]

A consistent IT2F preference is defined as:

Definition 3. An IT2F preference $\tilde{A}_{jk}$ is consistent if

$$\tilde{A}_{Best,j}, \tilde{A}_{jk} = \tilde{A}_{Best,k}, \tilde{A}_{jk} \times \tilde{A}_{k,Worst} = \tilde{A}_{jW}, j, k \epsilon N. \quad (4)$$

Suppose the optimal IT2F weighting vector is $\widetilde{W} = (\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_n)^T$. For all criteria weights, the IT2F weight of the best criteria is $\widetilde{w}_B$, and that of the worst criteria is $\widetilde{w}_W$. If the IT2FP is perfectly consistent, then it should have $\frac{\widetilde{w}_B}{\widetilde{w}_j} = \tilde{A}_{Bj}$ and $\frac{\widetilde{w}_j}{\widetilde{w}_W} = \tilde{A}_{jW}$.

Generally, it is difficult to obtain totally consistent IT2FPs. An optimal solution to obtain the highest consistency is to reduce the largest absolute gaps between $\left|\frac{\widetilde{w}_B}{\widetilde{w}_j} - \tilde{A}_{Bj}\right|$ and $\left|\frac{\widetilde{w}_j}{\widetilde{w}_W} - \tilde{A}_{jW}\right|$. After getting the IT2F criteria weights, a normalizing step is required, so the centroid of the IT2FSs is taken into account. Based on the preceding study, we build the following optimization model to find the best IT2F weights $\widetilde{W}^* = (\widetilde{w}_1^*, \widetilde{w}_2^*, \dots, \widetilde{w}_n^*)^T$, such that

$$\min \max_j \left\{ \left|\frac{\widetilde{w}_B}{\widetilde{w}_j} - \tilde{A}_{Bj}\right|, \left|\frac{\widetilde{w}_j}{\widetilde{w}_W} - \tilde{A}_{jW}\right| \right\}$$

$$s.t. \begin{cases} \sum_{j=1}^{n} C(\widetilde{w}_j) = 1 \\ \widetilde{w}_{j1}^U \le \widetilde{w}_{j1}^L, \widetilde{w}_{j3}^L \le \widetilde{w}_{j4}^U \\ \widetilde{w}_{j1}^L \le \widetilde{w}_{j2}^L \le \widetilde{w}_{j3}^L \\ \widetilde{w}_{j1}^U \le \widetilde{w}_{j2}^U \le \widetilde{w}_{j3}^U \le \widetilde{w}_{j4}^U \\ \widetilde{w}_{j1}^U \ge 0, j = 1,2,\dots,n \end{cases} \quad (5)$$

To prevent finding multiple optimal solutions [17] from the model (5), we can minimize the maximum absolute gaps between $\{|\widetilde{w}_B - \widetilde{w}_j \times \tilde{A}_{Bj}|\}$ and $\{|\widetilde{w}_j - \widetilde{w}_W \times \tilde{A}_{jW}|\}$. Suppose the maximum absolute gap is $\tilde{\delta}^* = [(\delta^*, \delta^*, \delta^*, \delta^*), (\delta^*, \delta^*, \delta^*)]$; then, we may convert Eq. (5) into the following optimization model:

$$\min \delta^*$$

$$s.t.\begin{cases} \sum_{j=1}^{n} C(\widetilde{w}_j) = 1 \\ \left|\widetilde{w}_{B1}^U - \widetilde{w}_{j1}^U \times \widetilde{w}_{B,j1}^U\right| \le \delta^*, \left|\widetilde{w}_{B2}^U - \widetilde{w}_{j2}^U \times \widetilde{w}_{B,j2}^U\right| \le \delta^*, \left|\widetilde{w}_{B3}^U - \widetilde{w}_{j3}^U \times \widetilde{w}_{B,j3}^U\right| \le \delta^*, \\ \left|\widetilde{w}_{B4}^U - \widetilde{w}_{j4}^U \times \widetilde{w}_{B,j4}^U\right| \le \delta^*, \left|\widetilde{w}_{B1}^L - \widetilde{w}_{j1}^L \times \widetilde{w}_{B,j1}^L\right| \le \delta^*, \left|\widetilde{w}_{B2}^L - \widetilde{w}_{j2}^L \times \widetilde{w}_{B,j2}^L\right| \le \delta^*, \\ \left|\widetilde{w}_{B3}^L - \widetilde{w}_{j3}^L \times \widetilde{w}_{B,j3}^L\right| \le \delta^*, \left|\widetilde{w}_{j1}^U - \widetilde{w}_{W1}^U \times \widetilde{w}_{j,W1}^U\right| \le \delta^*, \left|\widetilde{w}_{j2}^U - \widetilde{w}_{W2}^U \times \widetilde{w}_{j,W2}^U\right| \le \delta^*, \\ \left|\widetilde{w}_{j3}^U - \widetilde{w}_{W3}^U \times \widetilde{w}_{j,W3}^U\right| \le \delta^*, \left|\widetilde{w}_{j4}^U - \widetilde{w}_{W4}^U \times \widetilde{w}_{j,W4}^U\right| \le \delta^*, \left|\widetilde{w}_{j1}^L - \widetilde{w}_{W1}^L \times \widetilde{w}_{j,W1}^L\right| \le \delta^*, \\ \left|\widetilde{w}_{j2}^L - \widetilde{w}_{W1}^L \times \widetilde{w}_{j,W2}^L\right| \le \delta^*, \left|\widetilde{w}_{j3}^L - \widetilde{w}_{W1}^L \times \widetilde{w}_{j,W3}^L\right| \le \delta^*, \left|\widetilde{w}_{B3}^U - \widetilde{w}_{j3}^U \times \widetilde{w}_{B,j3}^U\right| \le \delta^*, \\ \widetilde{w}_{j1}^U \le \widetilde{w}_{j1}^L, \widetilde{w}_{j3}^L \le \widetilde{w}_{j4}^U, \widetilde{w}_{j1}^L \le \widetilde{w}_{j2}^L \le \widetilde{w}_{j3}^L, \widetilde{w}_{j1}^U \le \widetilde{w}_{j2}^U \le \widetilde{w}_{j3}^U \le \widetilde{w}_{j4}^U, \widetilde{w}_{j1}^U \ge 0, j = 1,2,\dots,n \end{cases} \tag{6}$$

Model (6)'s solution space is linear model to obtain IT2FSs weights. The optimal weights $(\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_n)^T$ and δ^* is obtained by solving model (6).

C.B. Consistency ratio for IT2FBWM

The consistency ratio (CR) is a popular and useful metric for measuring the degree of consistency in PRs. CR is proposed to test the IT2FBWM's reliability. When $\tilde{A}_{Bj} \times \tilde{A}_{jw} \neq \tilde{A}_{Bw}$, the IT2FBWM will be inconsistent. To guarantee the relation $\tilde{A}_{Bj} \times \tilde{A}_{jw} = \tilde{A}_{Bw}$, an IT2FSs $\tilde{\delta}$ such that $\tilde{\delta} = [(\tilde{\delta}, \tilde{\delta}, \tilde{\delta}, \tilde{\delta}), (\tilde{\delta}, \tilde{\delta}, \tilde{\delta})]$ is added so that the following equation makes sense:

$$\left(\tilde{A}_{Bj} - \tilde{\delta}\right) \times \left(\tilde{A}_{jw} - \tilde{\delta}\right) = \tilde{A}_{Bw} + \tilde{\delta} \tag{7}$$

Considering Eq. (7) and $\tilde{A}_{Bj} = \tilde{A}_{jw} = \tilde{A}_{Bw}$, we can rewrite this equation as

$$\left(\tilde{A}_{BW} - \tilde{\delta}\right) \times \left(\tilde{A}_{Bw} - \tilde{\delta}\right) = \tilde{A}_{Bw} + \tilde{\delta} \tag{8}$$

Eq. (8) can be derived as

$$\tilde{\delta}^2 - \left(1^* + 2\tilde{A}_{Bw}\right)\tilde{\delta} + \left(\tilde{A}_{Bw}^2 - \tilde{A}_{Bw}\right) = 0, \tag{9}$$

where $1^* = [(1,1,1,1),(1,1,1)]$ and $0^* = [(0,0,0,0),(0,0,0)]$.

$C(\tilde{A}_{Bw})$ can be utilized to compute the consistency index. $\tilde{\delta}$ can also be characterized by a crisp value δ; thus, Eq. (9) can modify to:

$$\delta - \left(1 + 2C\left(\tilde{A}_{Bw}\right)\right)\delta + \left(\left(C\left(\tilde{A}_{Bw}\right)\right)^2 - C\left(\tilde{A}_{Bw}\right)\right) = 0, \tag{10}$$

After solving the Eq.(10), we can use different values of $C\left(\tilde{A}_{Bw}\right)$ to obtain the smallest consistency and the corresponding maximum possible values δ (see Table 2). Therefore, CR is proposed to check the degree of consistency and the reliability of the attained weights [15]:

$$CR = \delta^*/CI, \tag{11}$$

where $CR \in [0,1], CR \to 0$ indicates greater consistency, and $CR \to 1$ indicates less consistency.

Table II. Consistency index for IT2FBWM [15]

LTs	*EI*	*WI*	*MI*	*MP*	*SI*	*SP*	*VS*	*VVS*	*EX*
centroids	1.0000	1.7751	3.3551	4.3403	5.7189	6.5797	7.3902	8.3475	8.4302
CI	0	0.1882	0.7537	1.3038	2.0756	2.8840	3.7304	4.3412	4.7937

C.C. Interval VIKOR method

The VIKOR is an optimization solution method for solving MCDM problems with different units and conflicting criteria [18]. Then, interval VIKOR method is extended by Sayadi [19].

Suppose *m* alternatives are denoted by D_1, D_2, …, D_m and n denotes the number of criteria.

$$D = \begin{matrix} & c_1 & c_2 & \cdots & c_n \\ D_1 & [d_{11}^U, d_{11}^L] & [d_{11}^U, d_{11}^L] & \cdots & [d_{11}^U, d_{11}^L] \\ D_2 & [d_{11}^U, d_{11}^L] & [d_{11}^U, d_{11}^L] & \cdots & [d_{11}^U, d_{11}^L] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ D_m & [d_{11}^U, d_{11}^L] & [d_{11}^U, d_{11}^L] & \cdots & [d_{11}^U, d_{11}^L] \end{matrix} \qquad (11)$$

The method contains the following stages:

The best d_j^* and worst d_j^- are calculated for all criteria. If the $j \in I$ is the benefit criterion and $j \in J$ is the cost criterion, then we have:

$$d_j^* = \left(\max_i d_{ij}^U \,|j \in I\right) or \left(\min_i d_{ij}^L \,|j \in I\right)$$

$$d_j^- = \left(\min_i d_{ij}^L \,|j \in I\right) or \left(\min_i d_{ij}^U \,|j \in I\right) \qquad (12)$$

An interval values of $S_i = [S_i^L, S_i^U]$ and $R_i = [R_i^L, R_i^U]$ for each alternative $(i = 1, 2, \dots, m)$ are computed:

$$S_i^L = \sum_{j=I} w_j \left(d_j^* - f_{ij}^U\right)/\left(d_j^* - d_j^-\right) + \sum_{j=J} w_j \left(d_j^* - d_{ij}\right)/\left(d_j^- - d_j^*\right), \qquad (13a)$$

$$S_i^U = \sum_{j=I} w_j \left(d_j^* - d_{ij}^L\right)/\left(d_j^* - d_j^-\right) + \sum_{j=J} w_j \left(d_{ij}^U - d_j^*\right)/\left(d_j^- - d_j^*\right) \qquad (13b)$$

$$R_i^L = \max_j \{w_j \left(d_j^* - d_{ij}^U\right)/\left(d_j^* - d_j^-\right)|j \in I\,, w_j \left(d_{ij}^L - d_j^*\right)/\left(d_j^- - d_j^*\right)|j \in J\} \qquad (14a)$$

$$R_i^U = \max_j \{w_j \left(d_j^* - d_{ij}^L\right)/\left(d_j^* - d_j^-\right)|j \in I\,, w_j \left(d_{ij}^L - d_j^*\right)/\left(d_j^- - d_j^*\right)|j \in J\} \qquad (14b)$$

where W_j indicates the weight of each criterion and represents its relative importance.

Compute the interval values $Q_i = \left[Q_i^L, Q_i^U\right], i = 1, 2, \dots, I$, by the relation

$$Q_i^L = v(S_i^L - S^*)/(S^- - S^*) + (1 - v)(R_i^L - R^*)/(R^- - R^*) \qquad (15a)$$

$$Q_i^U = v(S_i^U - S^*)/(S^- - S^*) + (1 - v)(R_i^U - R^*)/(R^- - R^*) \qquad (15b)$$

where $S^* = \min_i S_i^L$, $S^- = \max_i S_i^U$, $R^* = \min_i R_i^L$, $R^- = \max_i R_i^U$; and v is presented as a weight for the strategy of maximum group utility, whereas v is the weight of the individual regret.

According to the VIKOR approach, the option with the lowest Qi is the best option, and it is picked as a compromise solution. If these interval numbers do not intersect, the one with the lowest values is the minimum interval number.

IV. MODEL FORMULATION

A multi-objective integer linear programming supply chain model with multi-product, multi-mode, and multi-echelons is presented in this section. The presented SCN is of the forward type, with no consideration for reverse material flow.

Readers can consult [20] for more information. Suppliers deliver products to the manufacturer where they are processed in the supply chain under consideration. The processed materials are then transported to various retailers using various modes of transportation. Finally, retailers meet the needs of their customers.

In the face of the negative effects of risks, managers are always responsible for selecting actionable strategies to reduce expected risk losses and cost-risk impacts. Therefore, a set of actions is determined based on the set of risks that we have identified. In particular, in each supplier, a subset of actions, determined on the basis of the core set of actions, is allocated to the cost of the action to reduce risk. Similar to assessing the impact of risk, the cost effect of each action should be measured in proportion to the loss of financial resources that occurs in a particular supplier. The implementation of measures can also reduce the delays due to risks, the effect of which on time reduction is estimated according to each risk in different suppliers.

A. Model assumptions

- The above problem has been investigated as a multi-product, multi-period, and multi-mode supply chain network.
- All products are perishable.
- Risk only affects the selection of suppliers.
- Risk is defined as the probability of an adverse event occurring multiplied by the impact of that event.
- The total effect of risks on suppliers can be shown by summing the effect of all the risks that occur in that supplier.
- All measures to reduce secondary risks, once performed, will have the expected effects on cost and risk, and product failure.

B. Model parameters and variables

Sets

f Suppliers

a Manufacturer

r Retailers

c Customers

m Transportation modes

t Time periods

l Identified risks

k Identified responses to risk k

Parameters

P_{fjt} the cost per ton of product j purchased from supplier f in period t

KC_{fmaj}^{t} Unit transportation cost for product j in period t from supplier f to manufacturer a.

lc_{amrjt} Unit transportation cost for product j in period t from manufacturer a to retailer r by transportation mode m.

mc_{rmcjt} Unit transportation cost for product j in period t from retailer r to customer c by transportation mode m.

de_{fa} Transportation distance between supplier f and retailer r

ge_{ar} Transportation distance between manufacturer a and retailer r

he_{rc} Transportation distance between retailer r and customer c

n_{f}^{t} Fixed cost of supplier f in period t

b_{a}^{t} Fixed cost of manufacturer a in period t

e_{r}^{t} Fixed cost of retailer r in period t

$q_{flt}^{cost}/q_{flt}^{risk}/q_{flt}^{time}$ The amount of cost/risk/time loss in the selection of supplier f due to risk l in period t

$q_{fklt}^{scost}/q_{fklt}^{srisk}/q_{fklt}^{stime}$ The amount of cost/risk/time loss in the selection of supplier f due to the secondary response k to the secondary risk l in period t

$e_{fklt}^{cost}/e_{fklt}^{risk}/e_{fklt}^{time}$ The amount of cost/risk/time reduction in the selection of supplier f due to risk l in period t

$e_{fklt}^{scost}/e_{fklt}^{srisk}/e_{fklt}^{stime}$ The amount of cost/risk/time reduction in the selection of supplier f due to the secondary response k to the secondary risk l in period t

$q_{f}^{cost*^{t}}/q_{f}^{risk*^{t}}/q_{f}^{time*^{t}}$ Maximum expected loss in cost/risk/time in the selection of supplier f due to k response to risk l in period t

C. Objective functions

The first objective (Z_1) seeks to reduce total transportation costs as well as fixed costs. The first part is concerned with the cost of purchasing and transporting perishable products from suppliers to manufacturers. The objective function's second and third parts consider the transportation costs of sending perishable products from manufacturers to retailers and from retailers to customers. The fourth, fifth, and sixth parts are concerned with the fixed costs associated with suppliers, manufacturers, and retailers. The remaining parts show the cost of primary and secondary risk. The second objective (Z_2) seeks to reduce total response time. The third objective (Z_3) maximizes primary and secondary risk response.

$$Min\ Z_1 = \sum_f \sum_m \sum_a \sum_j \sum_t \left(P_{fjt} + KC_{fmaj}^{t}\, de_{fa}\right) QU_{fmaj}^{t} + \sum_a \sum_m \sum_r \sum_j \sum_t lc_{amrjt}\, ge_{ar} QN_{amrj}^{t} + \sum_r \sum_m \sum_c \sum_j \sum_t mc_{rmcjt}\, he_{rc} QA_{rmcj}^{t} + \sum_f \sum_t n_f^t . Z_f^t + \sum_a \sum_t b_a^t . I_a^t + \sum_r \sum_t e_r^t . Y_r^t + \left(\sum_f \sum_t \left(\sum_l q_{flt}^{cost} . Z_f^t - \sum_l \sum_k e_{fklt}^{cost} . ZI_{fkl}^{t} + \sum_l \sum_k c_{fklt}^{actioncost} . ZI_{fkl}^{t}\right)\right) + \left(\sum_f \sum_t \left(\sum_l \sum_k q_{fklt}^{scost} . ZI_{fkl}^{t} - \sum_l \sum_k e_{fklt}^{scost} . ZI'^{t}_{fkl} + \sum_l \sum_k c_{fklt}^{sactioncost} . ZI'^{t}_{fkl}\right)\right)$$

$$Min\ Z_2 = \sum_f \sum_m \sum_a \sum_j \sum_t \left(Pt_{fjt} + KT_{fmaj}^{t}\, de_{fa}\right) QU_{fmaj}^{t} + \sum_a \sum_m \sum_r \sum_j \sum_t lT_{amrjt}\, ge_{ar} QN_{amrj}^{t} + \sum_r \sum_m \sum_c \sum_j \sum_t mT_{rmcjt}\, he_{rc} QA_{rmcj}^{t} + \sum_f \sum_t nt_f^t . Z_f^t + \sum_a \sum_t bt_a^t . I_a^t + \sum_r \sum_t et_r^t . Y_r^t + \left(\sum_f \sum_t \left(\sum_l q_{flt}^{time} . Z_f^t - \sum_l \sum_k e_{fklt}^{time} . ZI_{fkl}^{t} + \sum_l \sum_k c_{fklt}^{actiontime} . ZI_{fkl}^{t}\right)\right) + \left(\sum_f \sum_t \left(\sum_l \sum_k q_{fklt}^{stime} . ZI_{fkl}^{t} - \sum_l \sum_k e_{fklt}^{stime} . ZI'^{t}_{fkl} + \sum_l \sum_k c_{fklt}^{sactiontime} . ZI'^{t}_{fkl}\right)\right)$$

$$Max\ Z_3 = \sum_f \left(\sum_l \sum_k e^{risk}_{fklt}.ZI^t_{fkl} - \sum_l \sum_k q^{srisk}_{fklt}.ZI^t_{fkl} + \sum_l \sum_k e^{srisk}_{fklt}.ZI'^{t}_{fkl}\right)/q^{risk*^t}_f.Z^t_f$$

D. Constraints

$$\sum_a \sum_m QU^t_{fmaj} \le Z^t_f.X_{fj} \quad \forall f \in F, j \in J, t \in T \quad (16)$$

$$\sum_r \sum_m QN^t_{amrj} \le I^t_a.O_{aj} \quad \forall a \in A, j \in J, t \in T \quad (17)$$

$$\sum_c \sum_m QA^t_{rmcj} \le Y^t_r.u_{rj} \quad \forall r \in R, j \in J, t \in T \quad (18)$$

$$\sum_f \sum_m QU^t_{fmaj} \ge \sum_r \sum_m QN^t_{amrj} \quad \forall a \in A, j \in J, t \in T \quad (19)$$

$$\sum_a \sum_m QN^t_{amrj} \ge \sum_c \sum_m QA^t_{rmcj} \quad \forall r \in R, j \in J, t \in T \quad (20)$$

$$\sum_{t'<t+\tau_j} \sum_r \sum_m QA^{t'}_{rmcj} = d_{cjt} \quad \forall c \in C, j \in J, t \in T \quad (21)$$

$$\sum_l q^{cost}_{flt}.Z^t_f - \sum_l \sum_k e^{cost}_{fklt}.ZI^t_{fkl} + \sum_l \sum_k q^{scost}_{fklt}.ZI^t_{fkl} - \sum_l \sum_k e^{scost}_{fklt}.ZI'^{t}_{fkl} \le q^{cost*^t}_f.Z^t_f \quad \forall f,t \quad (22)$$

$$\sum_l \sum_k e^{cost}_{fklt}.ZI^t_{fkl} - \sum_l \sum_k q^{scost}_{fklt}.ZI^t_{fkl} + \sum_l \sum_k e^{scost}_{fklt}.ZI'^{t}_{fkl} \ge 0 \quad \forall f,t \quad (23)$$

$$\sum_l q^{risk}_{flt}.Z^t_f - \sum_l \sum_k e^{risk}_{fklt}.ZI^t_{fkl} + \sum_l \sum_k q^{srisk}_{fklt}.ZI^t_{fkl} - \sum_l \sum_k e^{srisk}_{fklt}.ZI'^{t}_{fkl} \le q^{risk*^t}_f.Z^t_f \quad \forall f,t \quad (24)$$

$$\sum_l \sum_k e^{risk}_{fklt}.ZI^t_{fkl} - \sum_l \sum_k q^{srisk}_{fklt}.ZI^t_{fkl} + \sum_l \sum_k e^{srisk}_{fklt}.ZI'^{t}_{fkl} \ge 0 \quad \forall f,t \quad (25)$$

$$\sum_l q^{time}_{flt}.Z^t_f - \sum_l \sum_k e^{time}_{fklt}.ZI^t_{fkl} + \sum_l \sum_k q^{stime}_{fklt}.ZI^t_{fkl} - \sum_l \sum_k e^{stime}_{fklt}.ZI'^{t}_{fkl} \le q^{time*^t}_f.Z^t_f \quad \forall f,t \quad (26)$$

$$\sum_l \sum_k e^{time}_{fklt}.ZI^t_{fkl} - \sum_l \sum_k q^{stime}_{fklt}.ZI^t_{fkl} + \sum_l \sum_k e^{stime}_{fklt}.ZI'^{t}_{fkl} \ge 0 \quad \forall f,t \quad (27)$$

$$Z^t_f \ge ZI^t_{fkl} \quad \forall f,k,l,t \quad (28)$$

$$ZI^t_{fkl} \ge ZI'^{t}_{fkl} \quad \forall f,k,l,t \quad (29)$$

$$QU^t_{fmaj}, QN^t_{amrj}, QA^t_{rmcj} \ge 0 \quad \forall f,a,r,c,j,m,t \quad (30)$$

$$Z^t_f, I^t_a, Y^t_r, ZI^t_{fkl}, ZI'^{t}_{fkl} \in \{0,1\} \quad \forall f,a,r,k,l,t \quad (31)$$

Constraints (16), (17), and (18) address capacity constraints of suppliers, manufacturers, and retailer, respectively. Constraints (19) and (20) require that input products and output products be equal in each manufacturer and retailer (for each product in each time period). Constraint (21) ensures that each perishable product meets customer demand in each period.

Constraints (22) - (23) show the constraints on primary and secondary risk in the event of a supplier *f* being selected. There is also a relationship between the cost of primary risk and the cost of secondary risk, which is indicated by the constraint $Cost_{primary} \ge Cost_{secondary}$. Constraint (23) ensures that the cost of the secondary risk must be less than the cost of the primary risk. In addition, the cost of residual risk should be less than the amount allocated to the budget. The equation can describe the cost of residual risk.

Constraints (24)-(25) indicate that the total reduction in the risk level must be greater than or equal to zero. Constraints (26) and (27) are similar to the previous two constraints, except that they are defined for response time. Constraint (28) states that if supplier *f* is selected, then the initial risk can be quantified. In the model, two binary decision variables ZI^t_{fkl}

and ZI'^{t}_{fkl} are needed to indicate whether the primary and secondary responses selected to reduce the risks are required. Constraint (29) states that if the primary risk occurs, then the secondary risk can take value. Constraints (30)-(31) define non-negative variables and binary variables.

V. NUMERICAL EXAMPLE

In this section, we attempt to use the knowledge and experience of three decision-makers (DMs), including the production manager, sales manager, and quality control manager, to analyze and rate four suppliers for the Iranian food company. This food company was founded in 1991 and headquartered in Amol, Iran. It is known as a ground-breaking food production company in Iran. It produces various products, including milk, yogurt, cheese, butter, and ice cream. Suppliers of raw and recyclable goods are essential in this company. Therefore, the company intends to select the best supplier from the following criteria.

- Economic Criteria (1): Quality
- Social Criteria (2): Job creation
- Circular Criteria (3): Emissions of greenhouse gases from manufacturing processes and disposal activities
- Circular Criteria (4): Regulations and guidelines controlling the ecosystem
- Circular Criteria (5): Green packaging
- Circular Criteria (6): Eco-friendly and recyclable raw material
- Circular Criteria (7): Clean technology

Best (i.e., Quality criterion)-to-others and IT2F others-to-worst (i.e., Regulations and guidelines controlling the ecosystem criterion vectors are:

$$\tilde{A}_B = \left\{\begin{array}{c} [(1.000,1.000,1.000,1.000),(1.000,1.000,1.000)], \\ [(5.9686,6.750,7.1,8.2314),(6.7172,6.8889,7.1036)], \\ [(4.6893,5.50,6.20,6.9485),(5.6379,5.8889,6.0621)], \\ [(7.0136,7.65,8.00,8.7071),(7.5172,7.8125,8.0828)], \\ [(3.3101,4.25,5.05,6.0107),(4.4136,4.8900,5.0278)], \\ [(4.6893,5.50,6.20,6.9485),(5.6379,5.8889,6.0621)], \\ [(1.00,1.00,1.7184,2.6165),(1.000,1.0734,1.9266)] \end{array}\right\}$$

$$\tilde{A}_w = \left\{\begin{array}{c} [(7.0136,7.65,8.00,8.7071),(7.5172,7.8125,8.0828)] \\ [(1.4308,2.35,2.80,3.3968),(2.5172,2.6941,3.0828)] \\ [(3.3101,4.25,5.05,6.0107),(4.4136,4.8900,5.0278)] \\ [(1.000,1.000,1.000,1.000),(1.000,1.000,1.000)] \\ [(5.9686,6.750,7.1,8.2314),(6.7172,6.8889,7.1036)] \\ [(1.00,1.00,1.7184,2.6165),(1.000,1.0734,1.9266)] \\ [(3.3101,4.25,5.05,6.0107),(4.4136,4.8900,5.0278)] \end{array}\right\}$$

The optimal weights $\widetilde{W}$ are obtained by solving model (6). Also, the optimal δ^* is 0.0347, so CR=0.0042 and very close to 0 indicating high consistency.

$$\widetilde{W} = \begin{Bmatrix} [(0.0940,0.1049,0.1131,0.1134),(0.1060,0.1068,0.1102)] \\ [(0.0156,0.0197,0.0219,0.0.248),(0.0198,0.0205,0.0216)] \\ [(0.0185,0.0225,0.0269,0.0316),(0.0232,0.0240,0.0257)] \\ [(0.0068,0.0088,0.0103,0.0133),(0.0088,0.0092,0.0101)] \\ [(0.0214,0.0276,0.0348,0.0447),(0.0280,0.0289,0.0328)] \\ [(0.0185,0.0225,0.0269,0.0316),(0.0232,0.0240,0.0257)] \\ [(0.0492,0.0790,0.0784,0.0787),(0.0730,0.0798,0.0790)] \end{Bmatrix}$$

After calculating the weights of criteria and receiving the opinions of decision-makers from the evaluation of suppliers with the linguistic terms, the interval VIKOR method mentioned in section (3.3) is implemented, and the final ranking of suppliers is obtained (See Table 4).

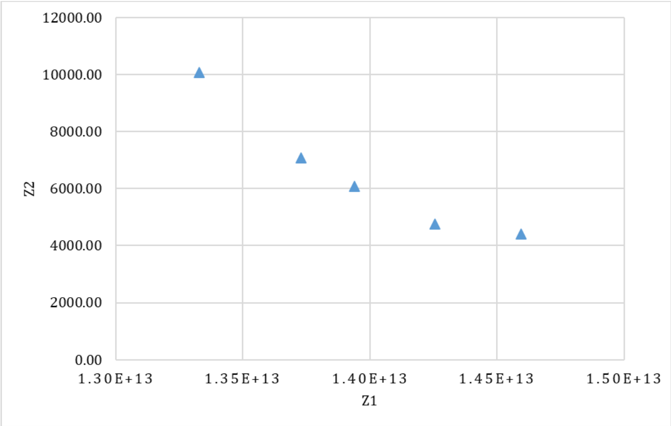
Table III. Evaluation four suppliers respect to seven criteria based on three DMs opinion

		C1	***C2***	***C3***	***C4***	***C5***	***C6***	***C7***
DM1	Supplier 1	WI	VS	MP	EX	VVS	EX	WI
	Supplier 2	MP	MI	WI	MP	VVS	MP	EI
	Supplier 3	SP	MI	SP	MP	WI	SI	EX
	Supplier 4	SI	SI	EI	EI	MP	EX	EX
DM2	Supplier 1	MP	MI	WI	VS	VS	SP	EX
	Supplier 2	SP	MI	EI	MP	EX	SP	WI
	Supplier 3	SP	MI	EX	VVS	VVS	EX	MI
	Supplier 4	EX	EI	SI	SI	EI	EX	MI
DM3	Supplier 1	EX	SP	VS	VS	MI	VS	SP
	Supplier 2	WI	VVS	EI	VVS	SI	EX	SP
	Supplier 3	EI	SP	VS	VS	VVS	MP	VVS
	Supplier 4	MI	SP	EI	EI	MI	SP	EX

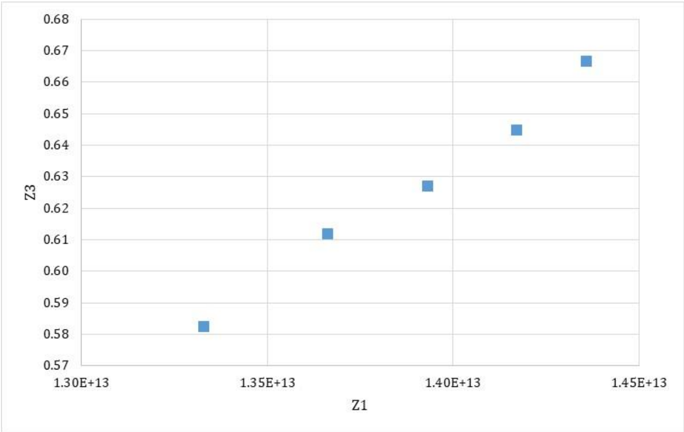
Table IV. Final ranking of suppliers

	$[S_i^L, S_i^U]$	$[R_i^L, R_i^U]$	$[Q_i^L, Q_i^U]$	***rank***
Supplier 1	[0.111,0.113]	[0.054,0.056]	[0.261,0.281]	2
Supplier 2	[0.243,0.246]	[0.117,0.117]	[0.990,0.997]	4
Supplier 3	[0.125,0.147]	[0.064,0.080]	[0.359,0.514]	3
Supplier 4	[0.067,0.068]	[0.029,0.029]	[0.000,0.002]	1

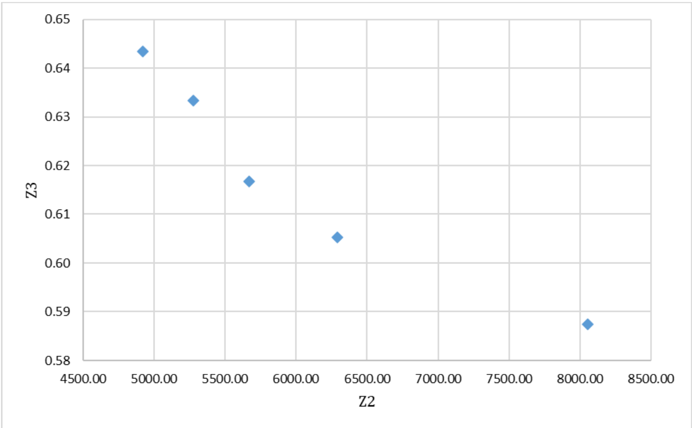
After evaluating the suppliers, the data obtained in the model presented in Section 4 are entered. The multi-objective model is solved using the augmecon2 method. A trade-off between objective functions is depicted in figure 2. As you can see in figure 2(a) by increasing total cost, the time response decreases. In figure 2(b) as total cost increases the risk response increases. In figure 2(c) as the response increases, the response time decreases.



a. A trade-off between the first and second objective function



b. A trade-off between the first and third objective function



c. A trade-off between the second and third objective function

Fig 2. A trade-off between objective functions

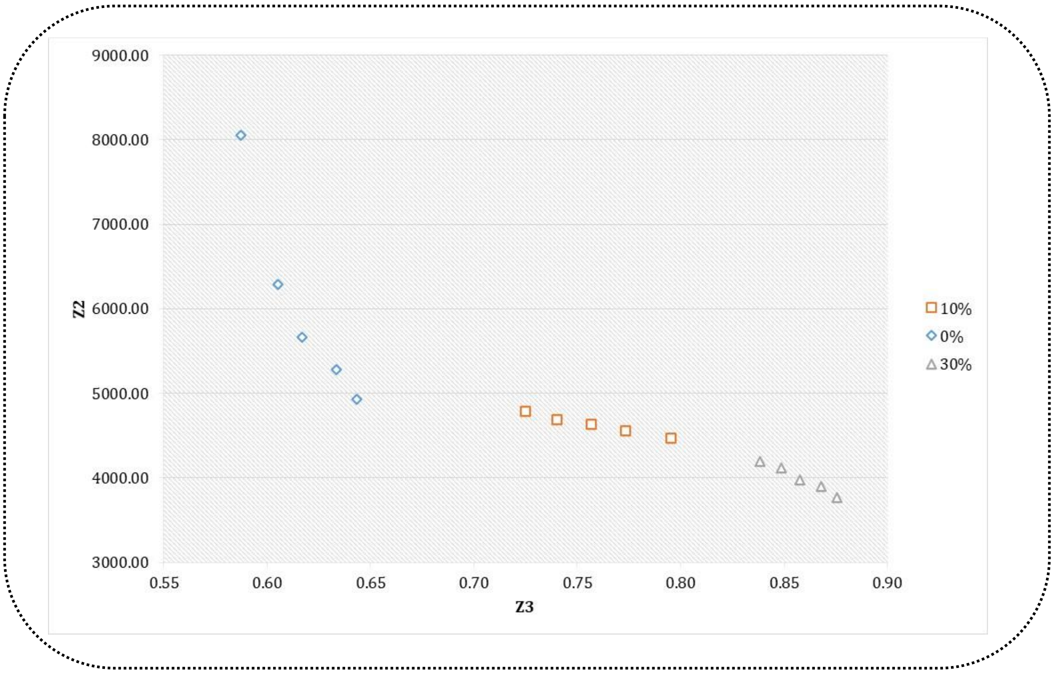


Fig 3. Sensitivity analysis on ($q_f^{cost*^t}$)

VI. CONCLUSION

The circular economy has a lot of choices for businesses to develop a long-term supply chain. Suppliers, as the main member of the supply chain from which operations originate, significantly affect network performance. In the CSC, this article discusses a new practical method for identifying sustainable suppliers. In addition, for the first time, circular and sustainable criteria are utilized to identify suppliers in the application of food company. The interval type-2 fuzzy BWM method is used to determine the weights of the criteria. Then, under uncertainty, suppliers are appraised and ranked using an interval VIKOR technique. Experts may simply assess suppliers using this method by expressing their opinion with linguistic terms. Using the proposed technique to evaluate four suppliers in an Iranian food company shows that it is successful and applicable. Each study has its own set of limitations and its own set of benefits and applications. These limitations lead to new study areas in the future. Our article is no exception, and it has its own set of limitations. One drawback of the suggested method is that it does not consider the interdependence of the criteria as a factor in the weighting process. The weights of the criteria will be more accurate if the interdependence between them is taken into account. As a future suggestion, we can see the effects of green on the objective function or use stochastic methods incorporated with decision method.

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