Resilience Supplier Selection and order allocation under uncertainty

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Abstract

Increasing the number of disasters around the world will decrease the performance of the supply chain. The decision makers should design resilience supply chain network which could encounter with disruptions. This paper develops an integrated resilience model of supplier selection and order allocation. Resiliency measures including quality, delivery, technology, continuity, environmental competences are explored for determining the Resilience Weight of suppliers. Fuzzy DEMATEL and ANP methods are applied to find overall performance of each supplier. Then, the developed mathematical model maximizes overall performance of suppliers while minimizes total cost of network. The proposed mathematical model helps the decision makers to select supplier and allocate the optimum order quantities by considering shortage. Since the disruptive incidents are inevitable events in real world problems, the impact of disruptions on suppliers, manufactures and retailers has been considered in the proposed model. Inherent uncertainties of parameters are taken into account to increase the compatibility of the approach with realistic environments. To tackle the uncertainty and multi-objectiveness of the proposed model, interval Method and TH aggregation function is adapted. The proposed model is validated through application to a real case study in a furniture company. Results demonstrate the usefulness and applicability of the proposed model.

Keywords: Resilience supply chain, Supplier selection, order allocation, Mathematical modeling, Uncertainty

1. Introduction

Rapid movements towards globalization, competitive marketplace, remarkable advances in technology, and high costumers' expectations have convinced companies to reduce costs and increase their competitive advantages [1]. A supply chain encompasses suppliers, manufacturers, distributers, retailers, and costumers which begins with purchasing raw materials and ends with consumption of final product by customer [2]. Due to the presence of various actors, decision making issues in the supply chain are more complex than other areas. In addition, decisions in supply chain management were classified into three categories including strategic, tactical, and operational level [3]. The main decisions in strategic level were partnership selection and supply chain network design which has the most extensive effect on the performance of the network [4]. Procurement [5], production [6], distribution planning [7], order allocation [8] challenges are the most important issues at the tactical level. Finally, at operational level decisions such as production and transportation scheduling are considered [9]. Unstable situations and unexpected incidents among supply chain actors force decision makers to recognize the optimal decision at any levels and situations. Therefore, they need to update supply side by choosing suppliers and allocating order jointly and rapidly [8].

Researches demonstrated that supplier selection (at strategic decision level) and order allocation (at tactical decision level) decisions have significance influence on the performance of the supply chain [10, 11]. The concern would be aroused when several supply chain have been disrupted due to disasters or crisis. The actors lost their resources and as results cannot deliver their products to next level in supply chain network [12]. To tackle this issue, decision makers have to consider the resilience features for choosing suppliers and determining order quantity. Despite the growing concern about disruption in supply chain network design problems, few scholars considered the resilience features to solve SS&OL problem [13].

This paper develops an integrated resilience model of SS&OL under uncertainty. At first stage, resilience measures are explored for choosing appropriate suppliers according to resilience features. Then the weight of each supplier is determined by applying two well-known multi criteria decision making methods i.e. fuzzy DEMATEL and fuzzy ANP. The RW of each supplier is used to develop a new fuzzy multi-objective mixed integer linear programming model. The proposed mathematical model helps the decision makers to select supplier and determine order size as well as shortage through minimizing total cost and maximizing resiliency of the supply chain. Since the disruptive incidents are inevitable events in real world problems, the impact of disruptions on suppliers, manufactures and retailers has been considered in the proposed model. In addition, inherent uncertainty of parameters is taken into account to increase the compatibility of the approach with realistic environments. To tackle the uncertainty and multi-objectiveness of the proposed model, interval Method and

TH aggregation function is adapted. The proposed model is validated through application to a real case study in a furniture company. The main contributions of the paper can be outlined as follows:

- Developing an integrated model for SS&OL by considering shortage;
- Considering the impacts of the disruptions on the actors of the supply chain;
- Evaluating suppliers with the resilience measures to increase the capability of supply chain against disasters or crisis;
- Validation of the proposed methodology through a case study in a furniture company.

2. Literature review

In today's competitive market, an organization has to optimize their business process through collaborating with other actors of supply chain. Each actor in the supply chain (i.e. supplier, manufacturer, distributer, and retailer) must aims to increase the total performance of the network [14]. One of the most important decisions which impacts all actors' performance is SS&OL decisions [15]. In recent years, this problem has been considered by many scholars as an integrated decision (strategic and tactical decision level) in supply chain area to achieve positional competitive advantage.

Several approaches have been developed for SS&OL problem. Since decision are made based on conflicting criteria, these approaches categorized into two main categories including analytical framework (or multi-attributes decision making methods) and multi-objective mathematical models [16]. In the literature many scholars utilized both categories simultaneously for selecting supplier and allocating order [17, 18]. For example, Hammami, Temponi [19] considered a global supplier selection problem in which price discounts and uncertain fluctuations of currency exchange rates play a crucial part. They formulated the problem as a mixed integer scenario based stochastic model in two stages. In the first stage the model seeks to select appropriate suppliers and total order quantity while in the second stage the model optimizes order size in different periods. Gören [20] proposed a hybrid decision framework for selecting supplier and allocating order quantity regarding sustainability factors. He applied fuzzy DEMATEL and Taguchi Loss Functions for calculating sustainability weight of each supplier. The results demonstrated the applicability and usefulness of such hybrid method [20]. Indeed, this paper develops a two steps decision framework that determining the RWs of the suppliers (by utilizing analytical framework), and then selecting supplier and allocating order quantity to them (developing a multi-objective mathematical model). Chai, Liu [21] reviewed the applications of different decision making techniques for SS&OL problem. They concluded that multi attribute decision making (MADM) methods such as AHP and ANP are the most frequently used due to their effectiveness in ranking. Moreover, fuzzy sets are capable approaches for dealing with uncertainty in SS&OL problem [22]. Keshavarz [23] reviewed the application of the fuzzy MADM methods for SS&OL in uncertain environment. The review included eleven well-known MADM methods that applied in 339 relevant problems. Their review shows that less attention has been paid to the fuzzy DEMATEL and ANP hybrid method for solving SS&OL problem. Although the fuzzy DEMATEL and AHP hybrid method was used more than fuzzy DEMATEL and ANP, the ANP method could comprising the whole interrelationship between selection factors [23]. Therefore, this paper applied the DEMATEL and ANP hybrid method for calculating the RW of the supplier.

Rezaei and Davoodi [24] presented two multi-objective models for solving SS&OL problem. They emphasized that new flexible methods should be developed to deal with hard constraints in multi-objective SS&OL problem. Furthermore, they proved that these two decisions must optimize jointly, due to the inherent interdependency between them [24]. Although shortage was considered in the model, other effective features between supply chain's actors not addressed (such as disruption, risk, delivery, and quality). Hajikhani, Khalilzadeh [15] proposed a fuzzy multi-objective mathematical programming model for SS&OL with pricing considerations. Different factors have been considered as objective function including purchase, transportation, and ordering costs, timely delivering. Fuzzy sets were used to solve the model under environmental uncertainties. They proposed risk and disruption are two major features for future research trend in SS&OL [15]. Recently, Gharaei, Pasandideh [10] developed a multi-objective mathematical model for SS&OL in supply chain with regard to imperfect quality products. They highlighted the impact of the imperfect quality products on the total performance of the supply chain (i.e. total inventory cost and profit). To increase the applicability of the model, the uncertainty of real problems was emerged in the stochastic constraints [10]. While the sensitivity analysis was used to show the trade-off between inventory cost and profit of the network, the impacts of other features (e.g. resilience and flexibility) not considered.

Although different aspects of the supply chain network design have been widely studied in the literature, review conducted by [25] shown that a small number of papers have studied resilience features for SS&OL. While the resilience features have been considered in other areas such as urban management [26, 27], logistics [28], and disaster operation management [29]. However, Sawik [30] proposed three mixed integer models to select supplier and allocate the quantity. His model aims to protect selected suppliers against disruptions and allocate emergency inventory among supply chain actors.

Fattahi [31] developed a resilience model of SS&OL under operational and disruption risk. He uses supplier fortification and option contract as well as risk constraint to develop resilience model. Different streams have been introduced to developed this study such as integration of supply chain decisions levels and modelling alternative resiliency factors. Vahidi, Torabi [32] present a new bi-objective two-stage programming model to solve SS&OL problem with operational and disruption risks. To improve the resilience level of the supply chain, they considered different resilience strategies such as backup suppliers from literature. A mixed possibilistic-stochastic mathematical model was developed to encounter with both disruptive and operational risk [32]. Although their model and solution method can handle the uncertainty of the real cases, the complexity of the approach decreased the applicability of the model. Furthermore, the developed model aims to increase the total performance of the supply chain through the overall resilience strategies. While it's not considered the resilience capability of each actor in supply chain for selecting supplier and allocating orders.

This paper contributes to the literature in several ways. First, an integrated mathematical model has been developed for strategic and tactical decision levels under uncertainty. To this end, supply chain network is designed with focusing on SS&OL problems in a dynamic multi-period, multi-sourcing, and multi-item environment. Second, resiliency measures are explored for measuring the RW of each supplier. Third, the impacts of the disruptions were considered on every actor in supply chain through suppliers to retailers. To the best of our knowledge, this paper is the first one in the literature which accounts these aspects for resilience SS&OL in a supply chain network design problem.

3. Integrated model of SS&OL

The aim of this paper is to design a resilience supply chain network with focus on SS&OA problem. In this manner, a two stage integrated approach is introduced. At the first stage the

RWs of suppliers are calculated. To this end, a set of resilience measurement is explored from literature and classified into five categories including *quality*, *delivery*, *technology*, *environmental competency*, and *continuity*. Then trapezoidal fuzzy DEMATEL is applied to find the strongest interdependencies among different measures. Following this, triangular fuzzy ANP is used to calculate the RW of supplier (which is known as overall performance of each supplier in network). At the second stage, a fuzzy multi objective mixed integer linear programming model is proposed. The proposed model aims to minimize total cost while maximize overall performance of the network. Figure 1 shows the proposed integrated approach schematically.

3.1. Problem description

Globalization and increased competition in markets has forced organizations to expand their market share for increasing their profit. In order to enhance quality and market share, organizations are enforced to select suppliers whose products are in higher quality and lower cost [33]. In fact, organizations not only should be able to produce various products according to costumers' needs and preferences and transport the products to costumer through a resilience and cost-effective network, but also should be able to purchase the required raw materials from efficient suppliers [34]. Possibility of disruption occurrence and the inherent uncertainty of different parameters in supply chain network in real cases have highlighted the complexity of the problem.

This paper considers a three level supply chain including supplier, manufacture, and retailer. Suppliers supply required raw materials for production in manufactures level and the final products are shipped to retailers. Fixed and variable costs are varied in different plants due to their technologies and resources. Each manufacture is capable of producing one or more products. Manufactures select the suppliers and determine order quantity for each raw material. Type and amount of transferred products from each manufacture to retailer should be determined.

<<Insert Figure 1 here>>

3.2. Calculating RW

The main objective of this stage is to obtain RW of suppliers. A list of resilience measures and indicators is explored by reviewing the relevant literature in supplier selection context. Table 1 reported the list of resilience measures for suppliers' resilience measurement. The interdependencies among resilience measures and indicators are calculated through a hybrid fuzzy MCDM method i.e. fuzzy DEMATEL and fuzzy ANP methods. Finally, the overall performance of each supplier is calculated based on interest parties viewpoints towards suppliers.

<<Insert Table 1>>

Decision makers or stakeholders of supply chain are asked to score the suppliers' resilience measures in respect to each indicator with the range of 1 to 9. Then, the final RW of the supplier (*i*) with respect to RM l can be calculated from Eq. (2)

$$n_{li} = \left[\left(\prod_{k=1}^{h} n_{lik}{}^{M_k} \right) \right]^{\frac{1}{\sum_{k=1}^{h} M_k}} \tag{2}$$

Where n_{lz} is the final score for supplier i in respect to RM l, n_{lzk} is the score given by stakeholder k to the supplier (i) resilience measure with respect to indicator l, and M_k is the importance of k-th stakeholder for the supply chain. Accordingly, the resilience weight of the supplier can be derived from Eq. (3)

$$OP_i = \sum_{l=1}^{n} n_{li} W_{fl} \tag{3}$$

Where OP_z denotes the RW of supplier z, and W_{fl} is the final weight of indicator f related to RM l, which is derived from fuzzy ANP method. A brief explanation of fuzzy DEMATEL and fuzzy ANP methods are provided in Appendix I.

3.3. SS&OA mathematical formulation

The proposed model is formulated as fuzzy multi-objective mixed integer linear programming model. The model seeks to select supplier and allocate the order quantity. The Resilience Weight of the supplier calculated from the previous stage, using as input parameter in the proposed model.

3.3.1. Assumptions

The following assumptions have been used to formulate the SS&OA problem:

- Planning horizon is divided into certain periods. Decisions are to be made for the beginning of the periods;

- Fixed costs and variable costs vary from plant to plant since the applied equipment and facilities in each plant is different. These costs may differ in each period;
- Each product is composed of several components which the types and quantities are specified according to BOM;
- For suppling each raw material one or more suppliers are available
- Manufacturer can purchase excessive materials in one period and transport to customers after production in the following periods;
- Manufacturer may face with shortage in a period and compensate in the following periods;
- Inventory amount and inventory shortage in all plants are zero at the beginning of the planning horizon;
- Excess products and shortage of products impose extra costs;
- Suppliers may meet plants' demands in subsequent periods (shortage is allowed);
- Suppliers may produce excessive products in a period and transport them to plants in following periods;
- Each plant has specified capacity;
- Disruption rates for each actor at each period are specified based on experts' experiences and judgments;
- In this model, time is not intended directly for transportation of materials and products. The effect of time is considered as transportation cost.

3.3.2. Notations

The following notations are used to formulate the SS&OA:

Indices:

i Index of supplier ($i=1,...,I$)
j Index of manufacturer ($j=1,...,J$)
k Index of material ($k=1,...,K$)
s Index of retailer ($s=1,...,S$)
n Index of product ($n=1,...,N$)
t Index of period ($t=1,...,T$)

Parameters:

$\tilde{P}_{jn}^{t}$ Production capacity of manufacturer j for product n in period t
$\tilde{P}_{sn}^{t}$ Capacity of retailer s for product n in period t

$\tilde{P}_{ik}^{t}$ Capacity of supplier i for supplying material k in period t

$\tilde{d}_{sn}^{t}$ Demand of retailer s for product n in period t

$\tilde{C}_{ijk}^{t}$ Transportation cost of material k from supplier i to manufacturer j in period t

$\tilde{\lambda}_{ijk}^{t}$ Purchasing cost of material k from supplier i for manufacturer j in period t

$\tilde{\gamma}_{jsn}^{t}$ Transportation cost of product n from manufacturer j to retailer s in period t

$\tilde{\chi}_{jn}^{t}$ Variable production cost of product n in manufacturer j in period t

$\tilde{q}_{j}^{t}$ Operational fixed cost of manufacturer j in period t

h_{s}^{t} Operational fixed cost of supplier s in period t

ω_{nk} Quantity of material k required to produce one unit of product n based on BOM

$\tilde{u}_{jn}^{t}$ Average disruption rate for manufacturer j and product n in period t

$\tilde{v}_{sn}^{t}$ Average disruption rate for retailer s and product n in period t

$\tilde{\xi}_{ik}^{t}$ Average disruption rate for supplier i and material k in period t

$\tilde{\varpi}_{jsn}^{t}$ Excessive production cost of product n in manufacturer j for retailer s in period t

$\tilde{\psi}_{jsn}^{t}$ Shortage cost of product n in manufacturer j for retailer s in period t

$\tilde{\varpi}_{ijk}^{\prime t}$ Excessive cost of material k from supplier i for manufacturer s in period t

$\tilde{\psi}_{ijk}^{\prime t}$ Shortage cost of material k from supplier i for manufacturer s in period t

Decision variable:

x_{ijk}^{t} Amount of material k ordered by manufacturer j to supplier i in period t

y_{jsn}^{t} Amount of product type n transported from manufacturer j to retailer s in period t

I_{jsn}^{t} Amount of excessive production of product n by manufacturer j for retailer s in period t

B_{jsn}^{t} Amount of shortage in production of product n by manufacturer j for retailer s in period t

$I_{ijk}^{\prime t}$ Amount of excessive purchasing of material k from supplier i for manufacturer s in period t

$B_{ijk}^{\prime t}$ Amount of shortage in purchasing of material k from supplier i for manufacturer s in period t

α_{ik}^{t} 1, if supplier i is selected for purchasing material k in period t; 0, otherwise;

β_{sn}^{t} 1, if retailer s is selected for selling product n in period t; 0, otherwise;

π_{jn}^{t} 1, if manufacturer j is selected for production product n in period t; 0, otherwise;

3.3.3. Problem formulation

The proposed fuzzy multi-objective mixed integer linear programming model for SS&OA problem is as follows:

$$Min\ f_1 = \sum_i \sum_j \sum_k \tilde{C}^t_{ijk} .x^t_{ijk} + \sum_i \sum_j \sum_k \tilde{\lambda}^t_{ijk} .x^t_{ijk} + \sum_j \sum_s \tilde{\gamma}^t_{jsn} .y^t_{jsn}$$
$$+ \sum_j (\tilde{\chi}^t_{jn} .\pi^t_{jn} . \sum_s y^t_{jsn}) + \sum_j \tilde{q}^t_j .\pi^t_{jn} + \sum_s h^t_s .\beta^t_{sn}$$
$$+ \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{n=1}^{N} (I^t_{jsn} .\tilde{\varpi}^t_{jsn} + B^t_{jsn} \tilde{\psi}^t_{jsn})$$
$$+ \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (I'^t_{ijk} .\tilde{\varpi}'^t_{ijk} + B'^t_{ijk} .\tilde{\psi}'^t_{ijk}) \tag{4}$$

$$Max\ f_2 = \sum_i \sum_j \sum_k OP_i .x^t_{ijk} \tag{5}$$

s.t.

$$\sum_j x^t_{ijk} \le \tilde{P}^t_{ik} .\alpha^t_{ik} \qquad \forall i,k,t \tag{6}$$

$$\sum_s \sum_{n=1}^{N} y^t_{jsn} \le \sum_{n=1}^{N} \tilde{P}^t_{jn} \pi^t_{jn} \qquad \forall j,t \tag{7}$$

$$\sum_{j=1}^{J} \sum_{n=1}^{N} y^t_{jsn} \le \sum_{n=1}^{N} \tilde{P}^t_{sn} \beta^t_{sn} \qquad \forall s,t \tag{8}$$

$$\sum_{i=1}^{I} \sum_{k=1}^{K} \omega_{nk} .x^t_{ijk} .(1-\tilde{\xi}^t_{ik}) = \sum_{s=1}^{S} (1-\tilde{u}^t_{jn}).y^t_{jsn} \qquad \forall j,n,t \tag{9}$$

$$\sum_{s=1}^{S} \sum_{j=1}^{J} (1-\tilde{u}^t_{jn}).y^t_{jsn} .\pi^t_{jn} = \sum_{s=1}^{S} \sum_{j=1}^{J} (1-\tilde{v}^t_{sn}).\beta^t_{sn} .y^t_{jsn} \qquad \forall n,t \tag{10}$$

$$\sum_{j=1}^{J} y^1_{jsn} - \sum_{j=1}^{J} I^1_{jsn} + \sum_{j=1}^{J} B^1_{jsn} - \tilde{d}^1_{sn} = 0 \qquad \forall s,n \tag{11}$$

$$\sum_{j=1}^{J} I^{(t-1)}_{jsn} - \sum_{j=1}^{J} B^{(t-1)}_{jsn} + \sum_{j=1}^{J} y^t_{jsn} = \sum_{j=1}^{J} I^t_{jsn} - \sum_{j=1}^{J} B^t_{jsn} + \tilde{d}^t_{sn} \qquad \forall s,n,t \ge 2,3,...,T \tag{12}$$

$$I^T_{jsn} = B^T_{jsn} = 0 \qquad \forall j,s,n \tag{13}$$

$$I^0_{jsn} = B^0_{jsn} = 0 \qquad \forall j,s,n \tag{14}$$

$$\sum_{i=1}^{I} x_{ijk}^{1} - \sum_{i=1}^{I} I_{ijk}'^{1} + \sum_{i=1}^{I} B_{ijk}'^{1} - \sum_{n=1}^{N} \omega_{nk} \sum_{s=1}^{S} y_{jsn}^{1} = 0 \qquad \forall j,k \tag{15}$$

$$\sum_{i=1}^{I} I_{ijk}'^{(t-1)} - \sum_{i=1}^{I} B_{ijk}'^{(t-1)} + \sum_{i=1}^{I} x_{ijk}^{t} = \sum_{i=1}^{I} I_{ijk}'^{t} - \sum_{i=1}^{I} B_{ijk}'^{t} + \sum_{n=1}^{N} \omega_{nk} \sum_{s=1}^{S} y_{jsn}^{t} \qquad \forall j,k,t \geq 2,3,\dots,T \tag{16}$$

$$I_{ijk}'^{T} = B_{ijk}'^{T} = 0 \qquad \forall j,k,i \tag{17}$$

$$I_{ijk}'^{0} = B_{ijk}'^{0} = 0 \qquad \forall k,i,j \tag{18}$$

$$\sum_{j=1}^{J} (1-\tilde{u}_{jn}^{t}).y_{jsn}^{t}.\pi_{jn}^{t} = (1-\tilde{v}_{sn}^{t}).\tilde{d}_{sn}^{t}.\beta_{sn}^{t} \qquad \forall s,t,n \tag{19}$$

$$x_{ijk}^{t}, y_{jsn}^{t}, I_{jsn}^{t}, B_{jsn}^{t}, I_{ijk}'^{t}, B_{ijk}'^{t} \in \mathbb{Z} \qquad \forall i,j,k,s,t,n \tag{20}$$

$$\alpha_{ik}^{t}, \beta_{sn}^{t}, \pi_{jn}^{t} \in \{0,1\} \qquad \forall i,j,k,s,n,t \tag{21}$$

The objective f_1 is to minimize total cost of supply chain. Total cost consisting of material transportation cost (from suppliers to plants), material purchasing cost (by manufacturer from supplier), product transportation cost (from manufacturer to retailers), variable production cost, and fixed costs (both manufacturer and retailer). The problem is a multi-period problem in which close relation exist between supplier and manufacturer in different periods. Hence, the two last terms of f_1 are considered as penalty cost for excessive and shortage in supply and production. The objective f_2 is to maximize the resilience performance of the network. The function is calculated by multiplying resilience weight (derived from first stage) with order amount for each supplier. It helps the model select suppliers with higher RW and increased the resilience level of the supply chain network. Eqs. (6) to (8) guarantee suppliers, plants, and retailers' capacity in each period respectively. As the problem is a three level supply chain network, two balance equations are formulated. Eqs. (9) and (10) are balance equations between suppliers and manufacturers, and between plants and retailers respectively. Since excessive products and materials and shortage in plants and suppliers level are considered in the problem, two midterm balance equations are developed for products and materials. Eq. (11) ensures balance between all products and retailers with shortage in production or excessive production during the first period. Eq. (12) transforms excess products and shortages from a period to the subsequent. Eqs. (13) and (14) ensures that amount of excess and shortage is zero at the beginning and end of the planning horizon. Eqs.

(11) to (14) are balance constraints for excess and shortage of products. Similarly, Eqs. (15) to (18) are balance constraints for excess and shortage of materials. Each retailer may order specific amount of each products to manufacturer in each period based on their customers' demands. Demand equation is formulated according to disruption rates and retailers' demands as Eq. (19). Finally Eqs. (20) and (21) enforce integer and binary restrictions on corresponding decision variables.

4. Solution Methodology

To cope with the uncertainty and multi-objectives aspects of the proposed SS&OA model, a two-phased approach is used. In the first phase, the methods of [45] and [46] are hybridized as [47] to convert the model into equivalent auxiliary crisp one. Then, in the second phase, TH method [48] is applied to find the final preferred compromise solution. To increase the readability of the paper, the transformation method [47] is introduced in Appendix II.

Considering the equivalent crisp model extracted from the previous section, following steps should be applied to find the preferred compromise solution.

Step1: Determine the positive ideal solution (PIS) and negative ideal solution (NIS) for each objective function by solving the corresponding MILP model.

$$f_1^{PIS} = \min f_1 \qquad f_1^{NIS} = \max f_1$$
$$f_2^{PIS} = \max f_2 \qquad f_2^{NIS} = \min f_2$$

In order to reduce computational complexity, the following rules are suggested In TH method [48]:

• Obtaining an approximate positive ideal solution for each objective function by solving the corresponding MILP heuristically to obtain a satisfactory feasible integer solution

• Instead of solving a separate MILP for determining each NIS, we can estimate them using the positive ideal solutions. Let v_η^* and $f_\eta\left(v_\eta^*\right)$ denote the decision vector associated with the PIS of η th objective function and the corresponding value, respectively. So, the related NIS could be estimated as follows:

$$f_\eta^{NIS} = \min\left\{f_1\left(v_1^*\right), f_2\left(v_2^*\right), f_3\left(v_3^*\right)\right\}$$

Step2: Specify a linear membership function for each objective function as follows:

$$\mu_1(x)=\begin{cases}1 & \text{if } f_1 < f_1^{PIS} \\ \dfrac{f_1^{NIS}-f_1}{f_1^{NIS}-f_1^{PIS}} & \text{if } f_1^{PIS} \le f_1 \le f_1^{NIS} \\ 0 & \text{if } f_1 > f_1^{NIS}\end{cases} \tag{28}$$

$$\mu_2(x)=\begin{cases}1 & \text{if } f_2 > f_2^{PIS} \\ \dfrac{f_2-f_2^{NIS}}{f_2^{PIS}-f_2^{NIS}} & \text{if } f_2^{NIS} \le f_2 \le f_2^{PIS} \\ 0 & \text{if } f_2 < f_2^{NIS}\end{cases} \tag{29}$$

***Step3*:** Convert the model into an equivalent single objective function using the following formulation:

$$\begin{aligned}&\max\ \sigma(v)=\beta\sigma_0+(1-\beta)\left(\theta_1\mu_1(v)+\theta_2\mu_2(v)\right)\\&s.t.\\&\qquad \sigma_0\le\mu_1(v)\\&\qquad \sigma_0\le\mu_1(v)\\&\qquad \mathrm{v}\in \mathrm{F}(v),\qquad \beta,\sigma_0\in[0,1]\end{aligned} \tag{30}$$

Where $\mu_\eta(v)$ and $\sigma_0=\min_\eta\{\mu_\eta(v)\}$ denote the satisfaction degree of ηth objective function and the minimum satisfaction degree of objectives, respectively. This formulation has a new achievement function defined as a convex combination of the lower bound for satisfaction degree of objectives(σ_0), and the weighted sum of these achievement degrees ($\mu_\eta(v)$) to ensure yielding an adjustable balanced compromise solution. Also, θ_η and β indicate the relative importance of the ηth objective function and the coefficient of compensation. The θ_η is determined by the decision maker based on her/his preference so that $\theta_1+\theta_2=1$. Also β controls the minimum satisfaction level of objectives as well as the compromise degree among the objectives implicitly.

***Step4*:** We solve the crisp model by the MIP solver. If the decision maker is satisfied with this current efficient compromise solution, stop. Otherwise, provide another efficient solution by changing the value of some controllable parameters β and α , and then go back to Step 1.

5. Case Study

In order to illustrate the application of the proposed integrated approach for supply chain network design, a case study conducted in a wood product manufacturer on the northern part of Iran is presented. The company produces wooden buffet and chest of drawers in two workshops. Main raw material for each product is MDF sheet with different thickness and width. According to bill of materials (BOM) for each product, required amount of materials for each product is shown in table 2. Inventory cost and cost of shortages for each workshop is assumed to be common. Cost of excessive production () and Cost of shortage in production () are triangular fuzzy numbers in which parameters have uniform distribution as (p=U[5000,8000],m=U[9000,12000],o=U[15000,20000]) and (p=U[80000,100000],m=U[120000,150000],o=[180000,200000]) respectively.

<<Insert Table 2 here>>

<<Insert Figure 2 here>>

The company can provide required raw materials from three suppliers (Sup_1, Sup_2, Sup_3). As stated before, the company has two workshops for manufacturing the products. Required data for each workshop is shown in table 3. Moreover three planning periods are considered. Since the two workshops are located in the same industrial zone, their transportation and purchasing costs are the same. In this case, three retailers are considered. Required data for one of the retailers are presented in table 4 and the remainder is omitted due to space limitation. Three experts expressed their opinion about the company's suppliers and the interdependencies among the MAs and the overall performance of suppliers are calculated based on their quoted data. The network derived from DEMATEL is shown in figure 2 and the overall performance of each supplier is shown in table 5. Other information including capacity, average disruption rate, purchasing and transportation costs are also shown in table 5.

<<Insert Table 3 here>>

<<Insert Table 4 here>>

<<Insert Table 5 here>>

The presented model solved based on different minimum acceptable possibility level (α) and different θ_η and β . Acceptable results for decision makers in the company calculated based on $\theta_1 = 0.8$, $\theta_1 = 0.2$, $\beta = 0.7$, $\alpha = 0.6$. The results are shown in table 6.

<<Insert Table 6 here>>

6. Conclusion

In this paper, an integrated model for supplier selection and order allocation was proposed focusing on a dynamic multi-period, multi-sourcing, and multi-item supply chain. Resilience Weight of suppliers was obtained based on explored *Resiliency Measures* through a hybrid fuzzy DEMATEL and ANP methods. The results were incorporated in a fuzzy multi objective mixed integer linear programming model. The proposed mathematical model aims to minimize the total cost while maximize the resilience performance of the supply chain network. The applicability and usefulness of the proposed approach was examined through a real case study on a wood manufacturer company with two workshops, three suppliers, and three retailers. Based on decision makers' opinion, the results are applicable for supply chain network design and it can help them to make a balance between supply and market side.

Future research could address the inherent uncertainty of the problem by different approaches such as mixed fuzzy stochastic problems. Furthermore, proposing disruption factors and their effects on network structures in the model can lead to a more practical approach. In addition, developing heuristics and meta-heuristics methods for solving large scale problems is another avenue for further research.

Appendix I.

AI.1. DEMATEL

DEMATEL method has been successfully applied in different areas such as e-learning, marketing strategy, service quality, safety problems, and supplier selection [21, 49]. DEMATEL method was founded based on graph theory. It uses matrix calculation to visualize the problem and calculate impact strength of existing relations [50]. In this paper trapezoidal fuzzy DEMATEL is applied to map the interdependencies among MAs and find corresponding impact strength. Fuzzy trapezoidal numbers are expressed as follows [51]:

$$d_{lu} = \left(d_{lu}^{1}, d_{lu}^{2}, d_{lu}^{3}, d_{lu}^{4}\right) = \left(\max\left\{\frac{2l-1}{2g+1}, 0\right\}, \frac{2l}{2g+1}, \frac{2u+1}{2g+1}, \min\left\{\frac{2u+2}{2g+1}, 1\right\}\right) \tag{1}$$

Where l , u , and g can be obtained according to following definitions:

Definition1. Let $S = \{s_0, s_1, ... s_g\}$ be a set of finite and totally ordered set where s_i is the ith linguistic term, $i \in \{0,1,...,g\}$, then S is called the linguistic term set and g+1 the cardinality of S.

Defenition2. Let $S = \{s_l, s_{l+1}, ... s_u\}$ where s_l and s_u are the lower and upper limits respectively and $l, u \in \{0, 1, ..., g\}$, then S is called uncertain linguistic term which can be expressed as $[s_l, s_u]$ where $u - l$ indicates the degree of fuzziness.

This paper follows the following fuzzy DEMATEL steps provided by [51, 52] to map the interdependencies among MAs:

Step1. Ask a committee of experts to express their viewpoints towards the relation between MAs with uncertain linguistic terms and calculate the average matrix;

Step2. Calculate the total relation matrix based on normalized initial direct relation matrix acquired from the average matrix.

Step3. Define a threshold value to construct impact relation map. In this paper, threshold value is defined by expert. However there are some algorithms such as mean de-entropy (MMDE) developed by [53] to set a proper threshold value.

Step4. Map the interdependencies among MAs base on the total relation matrix and the defined threshold value.

AI.2. Fuzzy ANP

ANP introduced by [54] includes all possible connections between elements which is a general form of top to bottom hierarchies' concept in AHP. In this paper fuzzy ANP is applied to capture experts' viewpoints towards different KPIs through pairwise comparisons to find weights of each KPI. According to previous step, each Ma may affect the other differently. Therefore, the novel cluster weighting proposed by [55] is applied in this paper to incorporate the DEMATEL results in the fuzzy ANP method. The fuzzy ANP steps are as follows:

Step1. Develop unweighted supermatrix through pairwise comparisons using fuzzy triangular numbers based on Table AI.1.

Step2. Calculate the weighted supermatrix via multiplying derived matrix from DEMATEL method by defuzzified unweighted supermatrix.

Step3. Rise the weighted supermatrix to limiting power to acquire global priority vectors which are weights of each KPI and denote it by W_f .

<< *Insert Table* Table AI.1 here>>

Appendix II.

4.1. Auxiliary Crisp Model

The expected interval (EI) and expected value (EV) of triangular fuzzy number $a \sim TFN\left(a^p, a^m, a^o\right)$ can be defined as follows [56]:

$$EI\left(a\right) = \left[E_1^a, E_2^a\right] = \left[\int_0^1 f_a^{-1}(x)\,dx, \int_0^1 g_a^{-1}(x)\,dx\right] = \left[\frac{1}{2}\left(a^p + a^m\right), \frac{1}{2}\left(a^m + a^o\right)\right] \qquad (22)$$

$$EV\left(a\right) = \frac{E_1^a + E_2^a}{2} = \frac{a^p + 2a^m + a^o}{4} \qquad (23)$$

According to [45] the equivalent crisp equation for $a_i x \geq b_i$ and $a_i x = b_i$ are as the following ones, respectively:

$$\left[(1-\alpha)E_2^{ai} + \alpha E_1^{ai}\right]x \geq \alpha E_2^{bi} + (1-\alpha)E_1^{bi} \qquad (24)$$

$$\begin{aligned} &\left[\left(1-\frac{\alpha}{2}\right)E_2^{ai} + \frac{\alpha}{2}E_1^{ai}\right]x \geq \frac{\alpha}{2}E_2^{bi} + \left(1-\frac{\alpha}{2}\right)E_1^{bi} \\ &\left[\frac{\alpha}{2}E_2^{ai} + \left(1-\frac{\alpha}{2}\right)E_1^{ai}\right]x \leq \left(1-\frac{\alpha}{2}\right)E_2^{bi} + \frac{\alpha}{2}E_1^{bi} \end{aligned} \qquad (25)$$

Where α is the minimum acceptable possibility level for imprecise parameters.

Now, consider the following fuzzy mathematical programming model:

$$\begin{aligned} &Min \quad z = \tilde{c}^t x \\ &s.t. \\ &\qquad a_i x \geq b_i, \quad i = 1, \ldots, \mathrm{p} \\ &\qquad a_i x = b_i, \quad i = p+1, \ldots, m \\ &\qquad x \geq 0 \end{aligned} \qquad (26)$$

Based on the definitions of expected value and expected interval, the equivalent crisp model of the above formulation is as follows:

$$
\begin{aligned}
&Min \quad z = EV\left(\tilde{c}\right)x \\
&s.t. \\
&\quad \left[\left(1-\alpha\right)E_{2}^{ai} + \alpha E_{1}^{ai}\right]x \geq \alpha E_{2}^{bi} + \left(1-\alpha\right)E_{1}^{bi}, \quad i = 1,\ldots,\mathrm{p} \\
&\quad \left[\left(1-\frac{\alpha}{2}\right)E_{2}^{ai} + \frac{\alpha}{2}E_{1}^{ai}\right]x \geq \frac{\alpha}{2}E_{2}^{bi} + \left(1-\frac{\alpha}{2}\right)E_{1}^{bi}, \quad i = p+1,\ldots,m \\
&\quad \left[\frac{\alpha}{2}E_{2}^{ai} + \left(1-\frac{\alpha}{2}\right)E_{1}^{ai}\right]x \leq \left(1-\frac{\alpha}{2}\right)E_{2}^{bi} + \frac{\alpha}{2}E_{1}^{bi}, \quad i = p+1,\ldots,m \\
&\quad x \geq 0
\end{aligned}
\tag{27}
$$

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Table1. Resilience measures for suppliers' resilience measurement

RM	indicators	Reference	RM	indicators	Reference
A_1: Quality	C_1: defect rate	[35]	A_2: Delivery	C_7: lead time	[36]
	C_2: durability	[37]		C_8: order fulfillment rate	[38]
	C_3: strength	[38]		C_9: responsiveness	[38]
	C_4: part safety	[39]	A_4: Technology	C_{16}: capability of R&D	[40]
	C_5: reusable	[16]		C_{17}: capability of	[40]

				design	
	C_6: customer service	[39]	A_5: Continuity	C_{18}: collaboration with other organizations	[41]
A_3: Environmental Competency	C_{10}: resource consumption	[42]		C_{19}: risk management culture	[43]
	C_{11}: environmental management system	[25]		C_{20}: adaptive capability	[41]
	C_{12}: carbon management competency	[25]		C_{21}: strategic risk planning	[43]
	C_{13}: green packaging	[44]		C_{22}: information sharing	[41]
	C_{14}: reduction of waste	[44]			
	C_{15}: eco design	[44]			

Table 2. Required amount of materials for each product

Product (n)	Raw Material (k)	Required Amount
chest of drawers (n=1)	MDF 16mm (k=1)	73000 cubic centimeters
	MDF 3mm (k=2)	6900 cubic centimeters
	Lace Wood (k=3)	8
wooden buffet	MDF 16mm (k=1)	61950 cubic centimeters
	MDF 25mm (k=4)	16852 cubic centimeters
	Lace Wood (k=3)	14
	Wood (k=5)	907 cubic centimeters

Table 3. Data for workshops

Workshop	Operational fixed cost		Product	Parameter	Period		
	period	$\tilde{q}_j^t$			1	2	3
1	1 (Oct)	p=U[50,55] m=U[40,50]	Chest of Drawers	Capacity ($\tilde{P}_{jn}^t$)	(16,20,24)	(8,18,22)	(12,16,20)
		o=U[35,40]		Variable production cost ($\tilde{\chi}_{jn}^t$)	(30,35,40)	(25,30,35)	(27,32,37)
	2 (Nov)	p=U[46,51] m=U[36,46]		Average disruption rate ($\tilde{u}_{jn}^t$)	(0.2,0.25,0.3)	(0.3,0.35,0.4)	(0.2,0.25,0.3)
		o=U[31,37]	Wooden Buffet	Capacity ($\tilde{P}_{jn}^t$)	(25,30,35)	(10,14,16)	(14,16,18)
	3 (Dec)	p=U[48,53]		Variable production cost ($\tilde{\chi}_{jn}^t$)	(55,60,65)	(50,55,60)	(52,57,62)
		m=U[38,48] o=U[32,36]		Average disruption rate ($\tilde{u}_{jn}^t$)	(0.2,0.25,0.3)	(0.3,0.35,0.4)	(0.2,0.25,0.3)
2	1 (Oct)	p=U[33,38]	Chest of Drawers	Capacity ($\tilde{P}_{jn}^t$)	(24,28,32)	(4,8,12)	(8,12,16)
		m=U[26,36] o=U[23,28]		Variable	(25,30,35)	(20,25,30)	(22,27,32)

				production cost ($\tilde{\chi}^{t}_{jn}$)			
	2 (Nov)	p=U[29,34] m=U[22,32]		Average disruption rate ($\tilde{u}^{t}_{jn}$)	(0.1,0.2,0.25)	(0.1,0.2,0.25)	(0.1,0.2,0.25)
		o=U[19,24]	Wooden Buffet	Capacity ($\tilde{P}^{t}_{jn}$)	(10,14,16)	(4,10,12)	(4,7,8)
	3 (Dec)	p=U[31,36] m=U[24,34]		Variable production cost ($\tilde{\chi}^{t}_{jn}$)	(65,70,75)	(60,65,70)	(62,67,72)
		o=U[21,26]		Average disruption rate ($\tilde{u}^{t}_{jn}$)	(0.1,0.2,0.25)	(0.1,0.2,0.25)	(0.1,0.2,0.25)

Table 4. Partial data for retailers

Retailer	Operational fixed cost		Product	Parameters	Period		
	period	$\tilde{\varpi}^{t}_{jsn}$			1	2	3
1	1 (Oct)	p=U[3,4] m=U[5,6] o=U[7,8]	Chest of Drawers	Capacity ($\tilde{P}^{t}_{sn}$)	(3,5,6)	(4,5,6)	(4,6,7)
				Demand ($\tilde{d}^{t}_{sn}$)	(7,8,10)	(8,10,12)	(8,10,12)
	2 (Nov)	p=U[4,5] m=U[6,7] o=U[8,10]		Transportation cost ($\tilde{\gamma}^{t}_{jsn}$)	(18,25,30)	(18,25,30)	(18,25,30)
	3 (Dec)	p=U[3,4] m=U[6,7] o=U[8,10]		Average disruption rate ($\tilde{v}^{t}_{sn}$)	(.02,.04,.08)	(.02,.04,.08)	(.02,.04,.08)

Table 5. Partial data for suppliers

Suppliers	Overall Performance	Parameters	Raw Materials				
			1	2	3	4	5
1	6.1812	Purchasing ($\tilde{\lambda}^{t}_{ijk}$)	(28,30,35)	(3,5,6)	(2,4,10)	(50,55,60)	(1200,130 0,1400)
		Transportation ($\tilde{C}^{t}_{ijk}$)	(3,5,7)	(1,2,3)	(1,2,3)	(6,8,10)	(20,30,50)
		disruption rate ($\tilde{\xi}^{t}_{ik}$)	(0.08,0.1,0 .12)	(0.08,0.1, 0.12)	(0.08,0.1, 0.12)	(0.08,0.1, 0.12)	(0.08,0.1, 0.12)
2	2.643	Purchasing ($\tilde{\lambda}^{t}_{ijk}$)	(26,28,33)	(2,4,6)	(3,4,8)	(45,50,52)	(1100,115 0,1250)
		Transportation ($\tilde{C}^{t}_{ijk}$)	(2,4,8)	(1,2,3)	(3,3,5)	(8,9,12)	(22,36,55)
		disruption rate ($\tilde{\xi}^{t}_{ik}$)	(0.1,0.12,0 .15)	(0.1,0.12, 0.15)	(0.1,0.12, 0.15)	(0.1,0.12, 0.15)	(0.1,0.12, 0.15)
3	4.325	Purchasing ($\tilde{\lambda}^{t}_{ijk}$)	(32,35,38)	(5,7,8)	(2,3,5)	(52,60,65)	(1400,150 0,1600)
		Transportation ($\tilde{C}^{t}_{ijk}$)	(6,7,8)	(3,4,5)	(1,2,3)	(9,11,13)	(25,35,46)
		disruption rate (	(0.02,0.05, 0.1)	(0.02,0.0 5,0.1)	(0.02,0.05 ,0.1)	(0.02,0.05 ,0.1)	(0.02,0.05 ,0.1)

		$\tilde{\xi}_{ik}^{t}$)					

Table 6. Acceptable results for decision makers in the company based on the proposed approach

Period	Workshop	Raw Material	Supplier			total cost of purchasing material	total cost of transportation materials	Product	Retailer			total production cost	total cost of transporting products
			1	2	3				1	2	3		
1	1	1	18400	15335	0	98130	153460	Chest of Drawers	3	3	5	3520000	335000
		2	16290	2176	0	90750	41252						
		3	89	0	273	1174	71	Wooden Buffet	6	5	5	9120000	612000
		4	4826	4021	0	257390	40218						
		5	269	224	0	163555	25640	Sum	9	8	10	12640000	947000
	2	1	0	0	20700	724500	144900	Chest of Drawers	5	5	7	4590000	545000
		2	0	2430	8640	70200	39420						
		3	109	128	0	948	602	Wooden Buffet	5	4	3	8040000	455000
		4	0	637	2265	18413	10340						
		5	0	0	303	120750	24150	Sum	10	9	10	12630000	100000
2	1	1	22080	18402	0	1177485	184152	Chest of Drawers	4	4	5	4160000	410000
		2	19548	2611	0	108900	49502						
		3	106	0	327	1408	85	Wooden Buffet	8	4	5	9690000	640000
		4	5791	4825	0	308868	48261						
		5	322	268	0	196266	30768	Sum	12	8	10	13850000	1050000
	2	1	0	16560	0	579600	115920	Chest of Drawers	6	6	7	5130000	605000
		2	1944	0	6912	56160	31536						
		3	0	87	102	758	481	Wooden Buffet	4	3	2	6030000	340000
		4	509	0	1812	14730	8272						
		5	242	0	0	96600	19320	Sum	10	9	9	11160000	945000
3	1	1	0	0	24840	869400	173880	Chest of Drawers	4	4	5	4150000	410000
		2	0	2916	10368	84240	47304						
		3	130	153	0	1137	722	Wooden Buffet	7	4	6	9710000	645000
		4	0	764	2718	22095	12408						
		5	0	0	363	144900	28980	Sum	11	8	11	13860000	1050000
	2	1	14720	12268	0	785064	122768	Chest of Drawers	6	6	7	5120000	620000
		2	13032	1740	0	72600	33001						
		3	71	0	218	940	57	Wooden Buffet	4	5	3	80500000	460000
		4	3860	3216	0	205912	32174						
		5	215	179	0	130844	20512	Sum	10	11	10	13170000	1080000

Table AI.1. Linguistic terms and the equivalent fuzzy numbers

Linguistic term	Membership function
Equally important	(1,1,3)
Moderately important	(1,3,5)
Important	(3,5,7)
Very important	(5,7,9)
Extremely important	(7,9,9)

Figures:

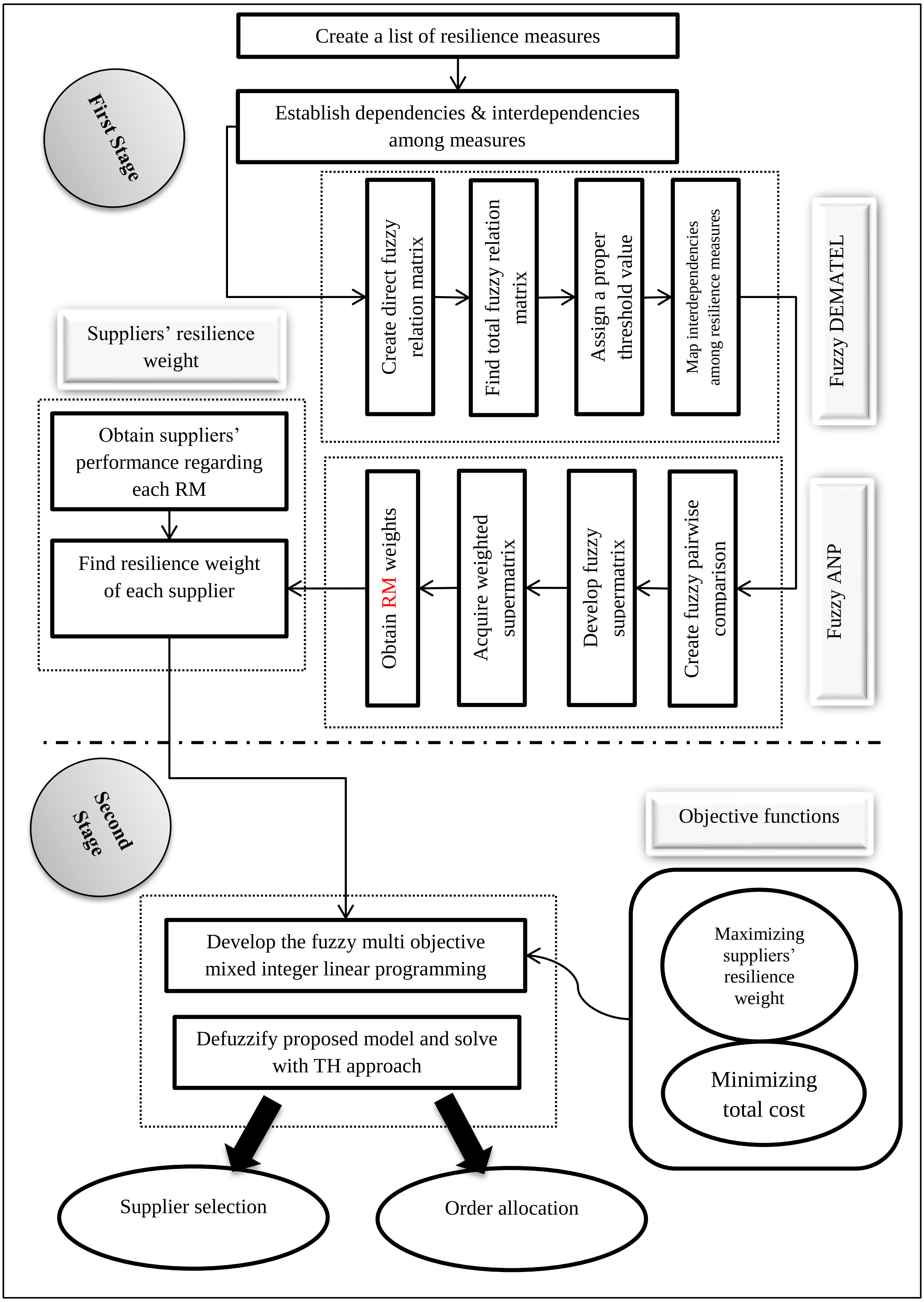

Figure 1. Proposed integrated approach for resilience SS&OA

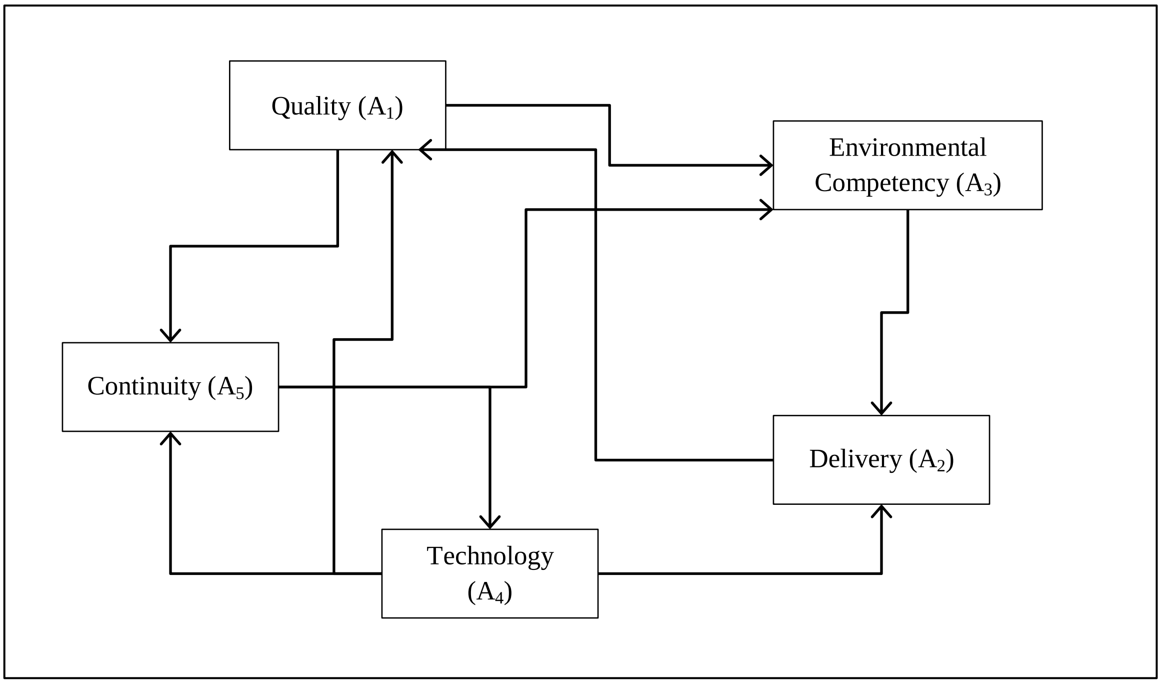

Figure 2. The network derived from DEMATEL