

ARAŞTIRMA MAKALESİ / RESEARCH ARTICLE

A FUZZY INTEGRATED APPROACH FOR RESILIENT SUPPLY CHAIN NETWORK DESIGN PROBLEM

ESNEK TEDARİK ZİNCİRİ AĞ TASARIMI PROBLEMİ İÇİN BULANIK BÜTÜNLEŞİK BİR YAKLAŞIM

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ABSTRACT

Supply chain disruptions can occur depending on internal and external factors and cause significant losses for all supply chain members. In order to cope with these disruptions, it is necessary to form resilient supply chain networks by pursuing holistic and proactive approaches. In the study, a resilient supply chain network design (SCND) problem is addressed under different disruption scenarios in a fuzzy environment by taking two of the most applied supply chain resilience strategies into account, namely the fortification of suppliers and using backup suppliers strategies. A two-stage integrated approach is proposed to solve the handled problem. The first stage includes the suppliers' evaluation process using the Fuzzy Analytic Hierarchy Process (F-AHP). A fuzzy Multi-Objective Linear Programming (F-MLP) model is developed to design the supply chain network in the second stage. The application of this approach is carried out on a realistic hypothetical problem and the results obtained and applicability of the proposed approach are discussed.

Keywords: Fuzzy Sets, Multi-Objective Linear Programming, Multi-Criteria Decision Making, Resilience, Supply Chain Network Design.


JEL Classification Codes: C44, C61.

ÖZ

Tedarik zinciri kesintileri, içsel ve dışsal faktörlere bağlı olarak ortaya çıkabilmekte ve tüm tedarik zinciri üyeleri için ciddi kayıplar doğurabilmektedir. Bu kesintiler ile başa çıkabilmek için bütüncül ve proaktif yaklaşımlar izlenerek esnek tedarik zincirleri oluşturmak gerekmektedir. Bu çalışmada esnek tedarik zinciri ağ tasarımı problemi, en çok uygulanan esnek tedarik zinciri oluşturma stratejilerinden tedarikçi güçlendirme ve yedek tedarikçi kullanma stratejilerini de göz önünde bulundurularak çeşitli kesinti senaryoları altında bulanık ortamda ele alınmıştır. Problemin çözümü için iki aşamalı bütüncül bir yaklaşım önerilmiştir. Yaklaşımın ilk aşaması, Bulanık Analitik Hiyerarşi Prosesi ile tedarikçilerin değerlendirilmesini içermektedir. İkinci aşama ise tedarik zinciri ağ tasarımı için bir Bulanık Çok-Amaçlı Doğrusal Programlama modelinin oluşturulmasını kapsamaktadır. Yaklaşımın uygulaması, gerçekçi olarak üretilen bir problem üzerinde yapılmıştır. Elde edilen sonuçlar ve yaklaşımın uygulanabilirliği ile ilgili değerlendirmeler sunulmuştur.

Anahtar Kelimeler: Bulanık Kümeler, Çok-Amaçlı Doğrusal Programlama, Çok Kriterli Karar Verme, Esneklik, Tedarik Zinciri Ağ Tasarımı.

JEL Sınıflandırma Kodları: C44, C61.

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1. INTRODUCTION

Supply chain disruptions can take place due to external factors such as earthquakes, floods, natural catastrophes, and/or human factors such as terrorist attacks, industrial accidents, failures in supply chain management, and they are often emerging suddenly (Ponomarov and Holcomb, 2009: 125; Snyder et al., 2016: 89). These disruptions, which may cause serious impacts and losses for companies, have attracted intensive attention in the supply chain literature recently (e.g., Scholten and Schilder, 2015; Ivanov, Pavlov, Dolgui, Pavlov and Sokolov, 2016; Hosseini et al., 2019).

Traditional supply chain management is not enough to reduce the risk of inevitable disruptions. It is necessary to follow proactive and holistic approaches to construct a resilient supply chain that will reduce the possibility of sudden disruptions and, when confronted with them, create the adaptive capacity to deal with them and turn the supply chain into a robust condition (Scholten and Schilder, 2015: 472; Kamalahmadi and Parast, 2016: 121).

The resilience concept is defined in the literature in different ways. Some of the studies have described the resilience as a system's ability to turn into a static/pre-disruption circumstance after an inevitable disruption occurs (Bhamra, Dani and Burnard, 2011: 5376; Scholten, Sharkey Scott and Fynes, 2014: 223), or return to a better state (Christopher and Peck, 2004: 2). On the other hand, some of the researchers have addressed the resilience more proactively and defined this term as a system's ability to decrease the probability, the effect of disruption, and recovering time to the normal state (Ponomarov and Holcomb, 2009: 131; Kamalahmadi and Parast, 2016: 121), even to a better condition (Ponis and Koronis, 2012: 925).

One of the most critical factors affecting companies' competitiveness is the network structure of the supply chain in which they take part. The resilience concept has drawn considerable interest in the context of the supply chain, including the SCND problem, and became one of the significant drivers of the network structure decisions. One of the aims of this study is to give insight into the current state of researches on supply chain resilience. For this purpose, an in-depth literature review has been conducted, focusing on the recent studies on this topic, and widely used supply chain resilience dimensions and strategies have been summarized. This study also aims to propose an integrated approach to handle a multi-objective SCND problem realistically under different disruption scenarios in a fuzzy environment. This approach uses resilience as a dimension affecting the selection of suppliers in the network and considers the options of applying supply chain resilience strategies to mitigate the effects of disruptions. A realistic hypothetical problem has been derived to employ this proposed approach. The first stage of this approach includes the creation of a candidate supplier list, determination of the evaluation criteria of these suppliers, and computation of both the evaluation criteria's importance degrees and the suppliers' scores by applying the F-AHP. In the second stage, an F-MLP model where the criteria used in the first stage are included in one of the objective functions is formulated to establish the SCND. The application of the model is carried out with a hypothetical problem. Various disruption scenarios are derived, and supply chain resilience strategies of fortification of suppliers, and having backup suppliers are considered. For each policy and no-disruption circumstances, supply chain network structures are obtained using the ϵ -constraint method.

The second section of this study introduces the literature review, including the studies that have addressed resilience within the scope of the supply chain. The resilience evaluation dimensions and the approaches followed in these studies are presented. The third section introduces the addressed problem and methodology in this study in detail. In the fourth section, the implementation results are provided. In the final section, the results are evaluated and discussed.

2. LITERATURE REVIEW

A resilient SCND necessitates assessing the resilience degree of a supply chain and applying appropriate resilience strategies when required. In the literature, there have been studies dealing with resilience within the frame of the supply chain and providing various resilience dimensions/criteria to evaluate the resilience degree of a supply chain. Also, several principles have been introduced to construct a resilient SCND. In Table 1, some of the widely used supply chain resilience dimensions and their definitions are presented.

Table 1. Supply Chain Resilience Dimensions

Dimensions	Definitions
Collaboration	The ability to effectively working with the other supply chain members to reduce uncertainty and mitigate risks (Christopher and Peck, 2004:9; Pettit, Fiksel and Croxton, 2010: 12).
Visibility	The ability of suppliers to share accurate and on-time data regarding inventories, demand, supply, and other logistics-related processes (Rajesh and Ravi, 2015: 347; Nooraie and Parast, 2015: 192).
Velocity	The rapidness of a supply chain responds to the demand changes (Christopher and Peck, 2014: 10). In the resilience context, velocity is the speed that a supply chain can get over a risk incident (Juttner and Maklan, 2011: 248).
Flexibility	The ability to easily react to disruptions affecting the supply network by maintaining cost and lead time control (Mohammed, Harris, Soroka and Nujoom, 2019b: 304).
Redundancy	To keep a number of resources reserved for use in case of disruption (Sheffi and Rice, 2005: 44).
Robustness	The ability to withstand disruptions without changing the existing structure of the supply chain (Wieland and Wallenburg, 2012: 890).
Risk management	To have a risk management culture and be able to recognize potential risks and take necessary actions to reduce them (Christopher and Peck, 2004: 11; Rajesh and Ravi, 2015: 345-346; Kamalahmadi and Parast, 2016: 126).
Agility	The ability to notice and react rapidly to unforeseen supply or demand changes (Christopher and Peck, 2004: 10; Purvis, Spall, Naim and Spieg, 2016: 581).
Leanness	The ability to satisfy the predictable demand without waste in an efficient way (Mohammed et al., 2019b: 304).

There have been various supply chain resilience strategies proposed in the literature to make supply chain networks more resilient. Table 2 provides a brief of the most encountered strategies in the literature and their explanations. In addition to the strategies in Table 2, postponement (Tang, 2006; Tang and Tomlin, 2008), development of business continuity plans (Torabi, Baghersad and Mansouri, 2015; Sabouhi, Pishvae and Jabalameli, 2018), and flexible supply contracts (Tang and Tomlin, 2008) are among the known supply chain resilience strategies.

Table 2. Supply Chain Resilience Strategies

Strategy	Explanation	Sources
Having backup suppliers	Contracting with reliable suppliers that provide materials/parts more expensive than the primary suppliers for being used in case of disruptions	Torabi et al. 2015; Ivanov et al., 2016; Sabouhi et al., 2018; Jabbarzadeh, Fahimnia and Sabouhi, 2018
Inventory and capacity buffers	Holding an amount of extra inventory for using after a disruption that may occur	Torabi et al., 2015; Ivanov et al., 2016; Sabouhi et al., 2018
Facility fortification	Protecting some of the supply chain members at different levels for reducing the impacts of disruptions (increasing the level of remained capacities)	Hasani and Khosrojerdi, 2016; Jabbarzadeh, Fahimnia, Sheu and Moghadam, 2016; Ivanov et al., 2016; Sabouhi et al., 2018
Capacity expansion	Increasing the capacities of facilities to compensate the lost capacities in case of disruptions	Ivanov et al., 2016; Jabbarzadeh et al., 2018; Sabouhi et al., 2018
Multiple sourcing	Using more than one source for decreasing the supply risk	Tang and Tomlin, 2008; Hasani and Khosrojerdi, 2016; Sabouhi et al., 2018; Jabbarzadeh et al., 2018

In many of the recent studies that have considered resilience as an evaluation criterion in the context of the supply chain, resilience dimension has been handled in conjunction with the sustainability dimension, in addition to the primary supplier selection criteria, such as cost, quality, reputation, delivery reliability, financial stability, technology capability (Rajesh and Ravi, 2015; Hosseini and Barker, 2016; PrasannaVenkatesan and Goh, 2016; Alikhani, Torabi and Altay, 2019; Lee, 2009).

Concern for environment (Chiou, Chan, Lettice and Chung, 2011; Rajesh and Ravi, 2015), green design capability (Amindoust, 2018; Alikhani et al., 2019) and energy efficiency (Amindoust, 2018; Awasthi, Govindan and Gold, 2018; Vahidi, Torabi and Ramezankhani, 2018) are among the most used sustainability sub-criteria in these studies.

Recent studies on supplier selection and order allocation indicate that resiliency has been analyzed in one or more elements' context, e.g., only supply-side (Hosseini et al., 2019), both supply and manufacturing tiers (Yoon,

Talluri, Yildiz, and Ho, 2018). There have been also studies examining this problem by applying several resilience strategies, such as using backup suppliers, enhancing suppliers' recovery capacities, having surplus inventory (Hosseini et al., 2019), having redundant and more flexible suppliers, improving the manufacturing capacity and increasing the inventory capacity (Yoon et al., 2018). PrasannaVenkatesan and Goh (2016) have handled this problem under various disruption risks, including geographical location, political stability, the flexibility of outputs, visibility, labor, and contractual based risks.

The recent studies addressing the resilient SCND problem have tended to handle this problem under realistic circumstances with various scenarios of disruptions with different sizes and impacts, aiming to optimize multi-objectives and comparing the performances of varying resilience strategies. The objective functions used in these studies include minimization of the total cost (e.g., Sadghiani, Torabi and Sahebjamnia, 2015; Torabi et al., 2015; Jabbarzadeh et al., 2016; Khalili, Jolai and Torabi, 2017; Zahiri, Zhuang and Mohammadi, 2017; Jabbarzadeh et al., 2018), the conditional value at risk (Khalili et al., 2017), social impacts, environmental impacts, and non-resiliency of the network (Zahiri et al., 2017); maximization of the supplier scores (Jabbarzadeh et al., 2018), supply network resilience level (Torabi et al., 2015), the total net present value (Hasani and Khosrojerdi, 2016).

Among the approaches followed in these studies, stochastic programming (Khalili et al., 2017; Jabbarzadeh et al., 2018; Sabouhi et al., 2018; Torabi et al., 2015), robust optimization (Sadghiani et al., 2015; Hasani and Khosrojerdi, 2016), hybrid robust-stochastic optimization modeling (Jabbarzadeh et al. 2016), fuzzy possibilistic-stochastic programming (Zahiri et al., 2017), stochastic fuzzy goal programming (Fahimnia and Jabbarzadeh, 2016) and hybrid multi-criteria decision making and F-MLP (Mohammed et al., 2019b) have been prominent.

In this study, the SCND problem is addressed under different disruption scenarios by applying different supply chain resilience strategies in the fuzzy environment using multi-objectives, in parallel with the recent studies' in this regard. The resilience dimension is taken into consideration on the supply side of the network structure. Resilience is one of the main evaluation criteria of the suppliers and has an important role in selecting the suppliers to be included in the network structure.

3. PROBLEM DESCRIPTION AND METHODOLOGY

The SCND problem addressed in this study includes supplier selection, and manufacturing facilities and distribution centers (DCs) establishment decisions to simultaneously aiming the minimization of total cost regarding all considered elements of the network, and maximization of suppliers' scores.

The network structure handled in this study, which is presented in Figure 1, comprises four stages. A manufacturing company (focal company) aims to meet the demands of market zones by simultaneously considering multi-objectives. This focal company needs to supply several raw materials to produce its products. It selects suppliers from the candidate list and determines which amounts of raw materials are provided. The focal company has some manufacturing facility alternatives in different locations. Their establishment costs and production capacities differ from each other. It transfers its products to the market zones via DCs located in different places and have different storage capacity and establishment costs.

The focal company aims to obtain a supply network structure satisfying the objectives that are the minimization of total costs (including costs of supplier selection, the establishment of manufacturing facilities and DCs, purchasing raw materials, all transportations in the network), and maximization of suppliers' scores, at the desired level.

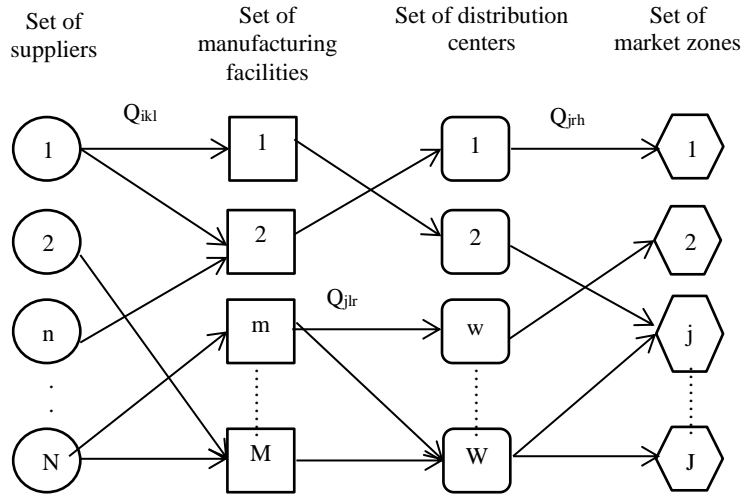


Figure 1.The Supply Network Structure

The problem is solved under various disruption scenarios that can affect suppliers' capacities, considering the options of applying resilience strategies of having backup suppliers and fortification of suppliers. These strategies have some opportunities to compensate for the losses in the suppliers' capacities in case of disruptions. Suppliers' fortification strategy allows increasing the production capacity of a primary supplier at a level by incurring a determined cost. Backup suppliers are the suppliers that are expected to sustain supplying raw materials in case of disruptions due to their high resiliency. They offer raw materials that are more expensive and at lower quantities than primary suppliers. In the problem addressed in this study, some suppliers may be included in both primary and backup supplier candidate lists. However, a supplier can be selected as either a primary or a backup supplier. The steps of the proposed methodology to tackle the discussed problem are given in Figure 2.

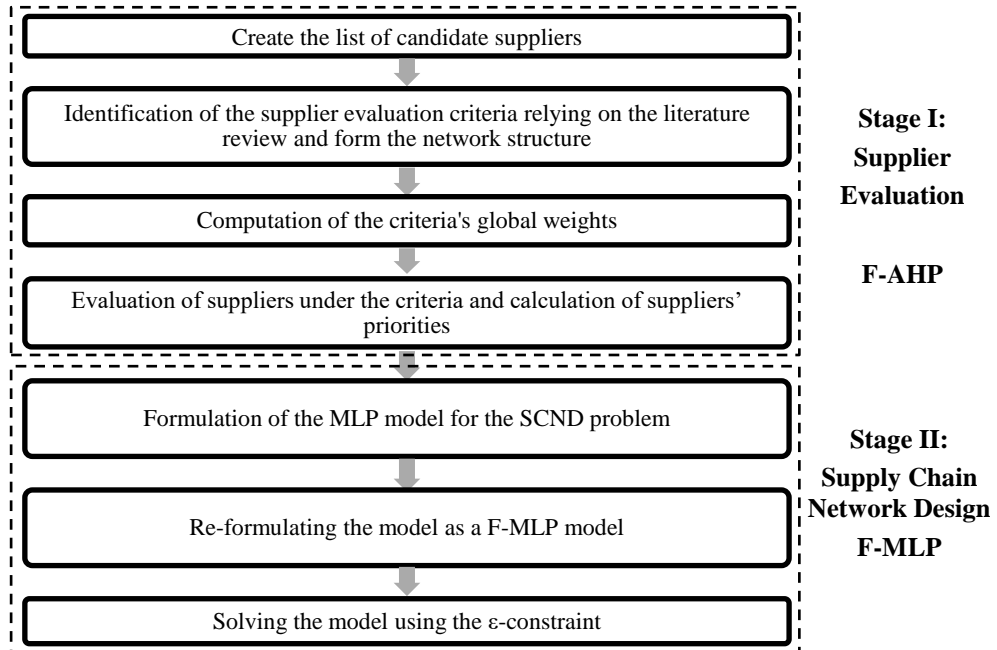


Figure 2. The Proposed Methodology

Stage I: Supplier Evaluation

In the first stage of the proposed methodology, F-AHP is used. F-AHP is a widely applied method for many years to the problems involving multiple and conflicting criteria and uncertainty in the decision-making environment, such as supplier selection. The method is also frequently used in recent studies that address the resilience concept in the context of supplier selection SCND, and supplier selection with order allocation problems (PrasannaVenkatesan and Goh, 2016; Awasthi et al., 2018; Mohammed, Harris and Govindan, 2019a), and maintains its popularity.

There have been different methodologies for calculation the fuzziness in the F-AHP (Shaw, Shankar, Yadav and Thakur, 2012). In this study, the extent analysis approach of Chang (1996) is adopted. The steps of F-AHP method to compute the importance weights of the main and sub-criteria are presented below:

Step 1: *Determination of the candidate suppliers, supplier selection criteria, and representing the hierarchical structure.*

Step 2: *Preparation of the criteria's pairwise comparison matrices by decision-makers individually.* The consistency of each decision-maker evaluation is checked, and if there is any inconsistency, the evaluation process is repeated until obtaining consistent comparison matrices. In the evaluation, triangular fuzzy numbers, one of the most preferred fuzzy numbers in the studies of fuzzy applications, are used. In pairwise comparisons, Lee (2009: 2885)'s fuzzy number and membership function scale are adopted.

Step 3: *Combining the decision-makers' evaluations.* A triangular fuzzy number \tilde{D} is calculated by aggregating the decision-makers' evaluations (Lee, 2009: 2885):

$$\tilde{D} = (n^-, n, n^+)$$

where

$$n^- = (\prod_{t=1}^s l_t)^{1/s} \quad \forall t = 1, 2, \dots, s \quad (1)$$

$$n = (\prod_{t=1}^s m_t)^{1/s} \quad \forall t = 1, 2, \dots, s \quad (2)$$

$$n^+ = (\prod_{t=1}^s u_t)^{1/s} \quad \forall t = 1, 2, \dots, s \quad (3)$$

and, (l_t, m_t, u_t) is the importance weight of decision-maker t .

Step 4: *Calculation of the crisp relative importance weights of the criteria by applying the Extent Analysis Method of Chang (1996).*

Degree of possibility $V(M_1 \geq M_2)$ is 1; if $l_1 \geq l_2$, $m_1 \geq m_2$, and $u_1 \geq u_2$. In other cases, the calculation below is used (Chang, 1996: 651):

$$V(M_2 \geq M_1) = \text{hgt}(M_1 \cap M_2) \quad (4)$$

$$= \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}$$

The fuzzy synthetic extent value regarding to the i -th object is (Chang, 1996: 650; Lee, 2009: 2882):

$$F_i = \sum_{j=1}^m M_{gi}^j \otimes [\sum_{i=1}^n \sum_{j=1}^m M_{gi}^j]^{-1} \quad (5)$$

$$\text{where } M_{gi}^j = [M_{ij}^-, M_{ij}, M_{ij}^+] \quad (6)$$

$$\sum_{j=1}^m M_{gi}^j = (\sum_{j=1}^m M_{ij}^-, \sum_{j=1}^m M_{ij}, \sum_{j=1}^m M_{ij}^+) \quad (7)$$

$$[\sum_{i=1}^n \sum_{j=1}^m M_{gi}^j]^{-1} = (\frac{1}{\sum_{i=1}^n \sum_{j=1}^m M_{ij}^+}, \frac{1}{\sum_{i=1}^n \sum_{j=1}^m M_{ij}}, \frac{1}{\sum_{i=1}^n \sum_{j=1}^m M_{ij}^-}) \quad (8)$$

A convex fuzzy number can be defined by:

$$V(F \geq F_1, F_2, \dots, F_k) = \min V(F \geq F_i) \quad i=1, 2, \dots, k \quad (9)$$

$$d(F_i) = \min V(F_i \geq F_k) = w_i' \quad k=1, 2, \dots, n \text{ and } k \neq i \quad (10)$$

The weight vector is:

$$W' = (w'_1, w'_2, \dots, w'_n)^T \quad (11)$$

After the weight vector's normalization, the weights of importance are obtained as below:

$$W = (w_1, w_2, \dots, w_n)^T \quad (12)$$

Step 5: *Obtaining priority weights for the alternatives.* Under each criterion, alternatives' normalized weight vectors are computed by applying the Steps of 2-4. These values are multiplied by the weight of the corresponding criterion. Alternatives' priority weights are calculated aggregating these weighted scores.

Stage II: Supply Chain Network Design

In this stage, the network structure is obtained by considering multi-objectives under derived disruption scenarios. The steps followed in this stage are as follows:

Step 6: *Formulating a multi-objective linear programming (MLP) model.*

In the literature, a large number of studies present multi-objective mathematical models for the SCND problem. Here, an MLP model is developed by adopting the basic structure of the model of Fahimnia and Jabbarzadeh (2016). In addition to their model, the model provided in this study considers supplier fortification and backup supplier usage strategies, and the constraint regarding the numbers of suppliers allowed to be selected. The assumptions, indices, parameters, and decision variables of the model are as follows:

Assumptions:

- Forecasted demand for products at market zones and all cost parameters except for lost sale costs are assumed to be uncertain.
- Lost sales are allowed for each product at each market zone.
- Potential locations of factories and DCs are known.

Indices:

- I : Raw materials set, indexed by i
J : Products set, indexed by j
K : Suppliers set, indexed by k
L : Manufacturing facilities (factories) set, indexed by l
R : DCs set, indexed by r
H : Market zones set, indexed by h
D : Disruption scenarios set, indexed by d
F : Fortifications set, indexed by f

Parameters:

- fc_k : Fixed selection cost of supplier k (€)
 fc_{kf} : Implementation cost of fortification level f to supplier k (€)
 fb_k : Contracting cost with backup supplier k (€)
 fc_l : Fixed establishment cost of facility l (€)
 fc_r : Fixed establishment cost of DC r (€)
 cap_{ik} : Capacity of primary supplier k for raw material i (unit)
 $capb_{ik}$: Capacity of backup supplier k for raw material i (unit)
 α_k^d : Lost capacity percentage of unfortified supplier k under disruption scenario d
 β_{kf}^d : Fortified supplier k's lost capacity percentage at fortification level f under scenario d
 cap_l : Production capacity of facility l (h)

- cap_r : Storage capacity of DC r (m^3)
 v_j : Volume of product j 's one unit (m^3)
 cp_{jl} : Production cost of product j 's one unit in facility l (€/unit)
 pt_{jl} : Production time of product j 's one unit in facility l (h)
 cp_{ikl} : A unit raw material i 's purchasing cost from supplier k to facility l (€/unit)
 cpb_{ikl} : A unit raw material i 's purchasing cost from backup supplier k to facility l (€/unit)
 a_{ikl} : Supplier k 's raw material i supply availability for facility l
 ct_{jlr} : Transportation cost of product j 's one unit from facility l to DC r (€/unit)
 ct_{jrh} : Transportation cost of product j 's one unit from DC r to market zone h (€/unit)
 cls_{jh} : Lost sales cost for a unit product j at market zone h (€/unit)
 d_{jh} : Demand forecasted of product j at market zone h (unit)
 q_{ij} : Required raw material i quantity to produce a unit of product j (unit)
 p_d : Probability of occurrence of disruption scenario d
 s_k : Aggregated score of supplier k under primary, sustainability, and resilience criteria
 M : Big number
 Z : The upper limit of suppliers allowed to be selected

Decision Variables

- X_k : 1, if supplier k is selected; 0, otherwise
 X_{kf} : 1, if supplier k is selected to be fortified by level f ; 0, otherwise
 Xb_k : 1, if supplier k is selected as a backup supplier; 0, otherwise
 X_l : 1, if facility l is established; 0, otherwise
 X_r : 1, if DC r is established; 0, otherwise
 Q_{jl}^d : Production amount of product j at facility l , under disruption scenario d
 Q_{ikl}^d : Raw material i amount that unfortified supplier k ships to facility l , under disruption scenario d
 Q_{fikl}^d : Raw material i amount that fortified supplier k ships to facility l , under disruption scenario d
 Q_{bikl}^d : Raw material i amount that backup supplier k ships to facility l , under disruption scenario d
 Q_{jlr}^d : Product j amount that facility l ships to DC r , under disruption scenario d
 Q_{jrh}^d : Product j amount that DC r ships to market zone h , under disruption scenario d
 Qls_{jh}^d : Product j lost sales amount at market zone h , under disruption scenario d

Objective Function 1

$$\begin{aligned}
 \text{Min } Z_1 = & \sum_{k \in K} fc_k X_k + \sum_{k \in K} \sum_{f \in F} fc_{kf} X_{kf} + \sum_{k \in K} fb_k Xb_k + \sum_{l \in L} fc_l X_l + \\
 & \sum_{r \in R} fc_r X_r + \sum_{d \in D} p_d \left[\sum_{i \in I} \sum_{k \in K} \sum_{l \in L} (cp_{ikl} (Q_{ikl}^d + Q_{fikl}^d) + cpb_{ikl} Q_{bikl}^d) + \sum_{j \in J} \sum_{l \in L} cp_{jl} Q_{jl}^d + \right. \\
 & \left. \sum_{j \in J} \sum_{l \in L} \sum_{r \in R} ct_{jlr} Q_{jlr}^d + \sum_{j \in J} \sum_{r \in R} \sum_{h \in H} ct_{jrh} Q_{jrh}^d + \sum_{j \in J} \sum_{h \in H} cls_{jh} Qls_{jh}^d \right]
 \end{aligned} \quad (13)$$

Objective Function 2

$$\text{Max } Z_2 = \sum_{k \in K} s_k (X_k + Xb_k) \quad (14)$$

Constraints

$$Q_{ikl}^d \leq M \cdot a_{ikl} X_k \quad \text{for all } i \in I, k \in K, l \in L, d \in D \quad (15)$$

$$Q_{fikl}^d \leq M \cdot a_{ikl} \sum_{f \in F} X_{kf} \quad \text{for all } i \in I, k \in K, l \in L, d \in D \quad (16)$$

$$Qb_{ikl}^d \leq M \cdot a_{ikl} Xb_k \quad \text{for all } i \in I, k \in K, l \in L, d \in D \quad (17)$$

$$\sum_{k \in K} X_k \leq Z \quad (18)$$

$$\sum_{f \in F} X_{kf} \leq X_k \quad \text{for all } k \in K \quad (19)$$

$$X_k + Xb_k \leq 1 \quad \text{for all } k \in K \quad (20)$$

$$\sum_{k \in K} (Q_{ikl}^d + Q_{fikl}^d + Qb_{ikl}^d) = \sum_{j \in J} q_{ij} Q_{jl}^d \quad \text{for all } i \in I, l \in L, d \in D \quad (21)$$

$$\sum_{l \in L} Qb_{ikl}^d \leq Xb_k \text{cap}_{ik} \quad \text{for all } i \in I, k \in K, d \in D \quad (22)$$

$$\sum_{j \in J} pt_{jl} Q_{jl}^d \leq \text{cap}_l X_l \quad \text{for all } l \in L, d \in D \quad (23)$$

$$\sum_{r \in R} Q_{jlr}^d = Q_{jl}^d \quad \text{for all } j \in J, l \in L, d \in D \quad (24)$$

$$\sum_{l \in L} Q_{jlr}^d = \sum_{h \in H} Q_{jrh}^d \quad \text{for all } j \in J, r \in R, d \in D \quad (25)$$

$$\sum_{r \in R} Q_{jrh}^d + Qls_{jh}^d = d_{jh} \quad \text{for all } j \in J, h \in H, d \in D \quad (26)$$

$$\sum_{l \in L} Q_{ikl}^d \leq (X_k - \sum_{f \in F} X_{kf}) (1 - \alpha_k^d) \text{cap}_{ik} \quad \text{for all } i \in I, k \in K, d \in D \quad (27)$$

$$\sum_{j \in J} \sum_{l \in L} v_j Q_{jlr}^d \leq \text{cap}_r X_r \quad \text{for all } r \in R, d \in D \quad (28)$$

$$\sum_{l \in L} Q_{fikl}^d \leq \text{cap}_{ik} \sum_{f \in F} X_{kf} (1 - \beta_{kf}^d) \quad \text{for all } i \in I, k \in K, d \in D \quad (29)$$

$$X_k, X_l, X_r, X_{kf}, Xb_k \in \{0,1\} \quad \text{for all } k \in K, l \in L, r \in R, f \in F \quad (30)$$

$$Q_{jl}^d, Q_{ikl}^d, Q_{fikl}^d, Qb_{ikl}^d, Q_{jlr}^d, Q_{jrh}^d, Qls_{jh}^d \geq 0 \quad \text{for all } j \in J, i \in I, k \in K, l \in L, r \in R, h \in H, d \in D \quad (31)$$

The first objective function, Eq. (13), implies the minimization of the total cost of the considered network. It includes the cost of supplier selection, supplier fortification at the selected level, contracting with backup suppliers, the establishment of facilities and DCs, production at facilities, raw material transportation from unfortified, fortified and backup suppliers to the facilities, product transportation from facilities to DCs and from DCs to market zones, and lost sales. The second objective function, Eq.(14), indicates the maximization of the overall supplier score. This score is equal to the sum of the obtained aggregated scores in the first stage of the suppliers selected as primary -unfortified or fortified- or backup.

Eqs. (15)-(17) ensures that for each scenario, supplier k can ship raw material i to facility l if it is available for supplying raw material i to facility l . Eq. (18) indicates that the total number of primary suppliers selected cannot be higher than the upper limit of suppliers allowed to be chosen. Eq. (19) guarantees that the fortification of a supplier at only one level is possible only if it is selected as a supplier. Eq. (20) refers that a supplier can be chosen either as a primary or backup supplier. Eq. (21) indicates that for each scenario, the total raw material i amount provided from unfortified, fortified, and backup suppliers to facility l must be equal to the usage quantity of raw material i for all products produced in facility l . The total i -th raw material amount transferred from backup supplier k to all factories cannot exceed the supply capacity of that backup supplier for the raw material i is expressed by Eq. (22). Eq.(23) guarantees that for each scenario, production time in the facility l allocated to all products cannot be higher than the production capacity of facility l . The total product j amount shipped from facility l to all DCs for each scenario must be equal to the production quantity of product j at facility l is expressed in Eq. (24). Eq. (25) indicates that for each scenario, the total quantity of product j shipped from all factories to DC r must be equal to the total product amount shipped from DC r to market zone h . For each scenario, product j 's demand at market zone h must be equal to the total amount of product j sent from all DCs to market zone h and lost sales quantity of that product at that market zone is ensured by Eq. (26). Eq. (27) states that raw material i amount sent from supplier k to all the factories is limited to the supplier k 's available capacity in the scenario d . For each scenario, the amount of all products shipped from all factories to DC r cannot surpass DC r 's storage capacity is expressed in Eq. (28). Eq. (29) represents that under scenario d , if a supplier k is selected to be fortified at the level u , the raw material I amount shipped from that supplier is limited to its remained capacity under that fortification level u . Eq. (30) and (31) state the binary decision variables and non-negativity constraints.

Step 7: Reformulating the model as an F-MLP model

To reflect the uncertainty in the real world, parameters including costs of supplier selection, fortification of primary suppliers, contracting with backup suppliers, factory, and DC establishing, production cost of products at facilities, purchasing from primary and backup suppliers, transportation from facilities to DCs, and from them to market zones, and market zones' demands are handled as uncertain in this study. After fuzzification, the minimization of total cost objective function and demand constraint are expressed as (13') and (26'), respectively.

$$\begin{aligned} \text{Min } Z_1 \cong & \sum_{k \in K} \tilde{f}c_k X_k + \sum_{k \in K} \sum_{f \in F} \tilde{f}c_{kf} X_{kf} + \sum_{k \in K} \tilde{f}b_k Xb_k + \sum_{l \in L} \tilde{f}c_l X_l + \\ & \sum_{r \in R} \tilde{f}c_r X_r + \sum_{d \in D} p_d \left[\sum_{i \in I} \sum_{k \in K} \sum_{l \in L} (\tilde{c}p_{ikl} (Q_{ikl}^d + Qf_{ikl}^d) + \tilde{c}p_{b_{ikl}} Qb_{ikl}^d) + \sum_{j \in J} \sum_{l \in L} \tilde{c}p_{jl} Q_{jl}^d + \right. \\ & \left. \sum_{j \in J} \sum_{l \in L} \sum_{r \in R} \tilde{c}t_{jlr} Q_{jlr}^d + \sum_{j \in J} \sum_{r \in R} \sum_{h \in H} \tilde{c}t_{jrh} Q_{jrh}^d + \sum_{j \in J} \sum_{h \in H} \tilde{c}l_{sjh} Ql_{sjh}^d \right] \end{aligned} \quad (13')$$

$$\sum_{r \in R} Q_{jrh}^d + Ql_{sjh}^d = \tilde{d}_{jh} \quad \text{for all } j \in J, h \in H, d \in D \quad (26')$$

To convert fuzzy parameters into crisp values, the weighted average method (Liang, 2006; Torabi and Hassini, 2008), one of the most applied methods in the literature, has been applied. The weights for the most pessimistic (p), the most likely (m), and the most optimistic (o) values are used as $w_1 = 1/6$, $w_2 = 4/6$, $w_3 = 1/6$ (respectively). And the minimum likelihood, β , is used as 0.5. As an example of the conversion of fuzzy parameters, the converted demand constraint is given in Eq. (26'').

$$\sum_{r \in R} Q_{jrh}^d + Ql_{sjh}^d = \frac{d_{jh}^p + 4d_{jh}^m + d_{jh}^o}{6} \quad \text{for all } j \in J, h \in H, d \in D \quad (26'')$$

The resulting equivalent crisp model, including both fortification of suppliers and backup supplier usage strategies, is as follows:

$$\begin{aligned} \text{Min } Z_1 = & \sum_{k \in K} \left(\frac{f_{c_k}^p + 4f_{c_k}^m + f_{c_k}^o}{6} \right) X_k + \sum_{k \in K} \sum_{f \in F} \left(\frac{f_{c_{kf}}^p + 4f_{c_{kf}}^m + f_{c_{kf}}^o}{6} \right) X_{kf} + \sum_{k \in K} \left(\frac{f_{b_k}^p + 4f_{b_k}^m + f_{b_k}^o}{6} \right) Xb_k \\ & + \sum_{l \in L} \left(\frac{f_{c_l}^p + 4f_{c_l}^m + f_{c_l}^o}{6} \right) X_l + \sum_{r \in R} \left(\frac{f_{c_r}^p + 4f_{c_r}^m + f_{c_r}^o}{6} \right) X_r + \sum_{d \in D} p_d \left[\sum_{i \in I} \sum_{k \in K} \sum_{l \in L} \left(\frac{c_{p_{ikl}}^p + 4c_{p_{ikl}}^m + c_{p_{ikl}}^o}{6} \right) (Q_{ikl}^d + \right. \\ & \left. Qf_{ikl}^d) + \left(\frac{c_{p_{b_{ikl}}}^p + 4c_{p_{b_{ikl}}}^m + c_{p_{b_{ikl}}}^o}{6} \right) Qb_{ikl}^d + \sum_{j \in J} \sum_{l \in L} \left(\frac{c_{p_{jl}}^p + 4c_{p_{jl}}^m + c_{p_{jl}}^o}{6} \right) Q_{jl}^d + \right. \\ & \left. \sum_{j \in J} \sum_{l \in L} \sum_{r \in R} \left(\frac{c_{t_{jlr}}^p + 4c_{t_{jlr}}^m + c_{t_{jlr}}^o}{6} \right) Q_{jlr}^d + \sum_{j \in J} \sum_{r \in R} \sum_{h \in H} \left(\frac{c_{t_{jrh}}^p + 4c_{t_{jrh}}^m + c_{t_{jrh}}^o}{6} \right) Q_{jrh}^d + \sum_{j \in J} \sum_{h \in H} \tilde{c}l_{sjh} Ql_{sjh}^d \right] \end{aligned} \quad (32)$$

$$\text{Max } Z_2 = \sum_{k \in K} s_k (X_k + Xb_k) \quad (33)$$

Subject to:

$$Q_{ikl}^d \leq M \cdot a_{ikl} X_k \quad \text{for all } i \in I, k \in K, l \in L, d \in D \quad (34)$$

$$Qf_{ikl}^d \leq M \cdot a_{ikl} \sum_{f \in F} X_{kf} \quad \text{for all } i \in I, k \in K, l \in L, d \in D \quad (35)$$

$$Qb_{ikl}^d \leq M \cdot a_{ikl} Xb_k \quad \text{for all } i \in I, k \in K, l \in L, d \in D \quad (36)$$

$$\sum_{k \in K} X_k \leq Z \quad (37)$$

$$\sum_{f \in F} X_{kf} \leq X_k \quad \text{for all } k \in K \quad (38)$$

$$X_k + Xb_k \leq 1 \quad \text{for all } k \in K \quad (39)$$

$$\sum_{k \in K} (Q_{ikl}^d + Qf_{ikl}^d + Qb_{ikl}^d) = \sum_{j \in J} q_{ij} Q_{jl}^d \quad \text{for all } i \in I, l \in L, d \in D \quad (40)$$

$$\sum_{l \in L} Qb_{ikl}^d \leq Xb_k \cdot c_{apb_{ik}} \quad \text{for all } i \in I, k \in K, d \in D \quad (41)$$

$$\sum_{j \in J} p_{t_{jl}} Q_{jl}^d \leq c_{apj} X_l \quad \text{for all } l \in L, d \in D \quad (42)$$

$$\sum_{r \in R} Q_{jlr}^d = Q_{jl}^d \quad \text{for all } j \in J, l \in L, d \in D \quad (43)$$

$$\sum_{l \in L} Q_{jlr}^d = \sum_{h \in H} Q_{jrh}^d \quad \text{for all } j \in J, r \in R, d \in D \quad (44)$$

$$\sum_{r \in R} Q_{jrh}^d + Ql_{sjh}^d = \frac{d_{jh}^p + 4d_{jh}^m + d_{jh}^o}{6} \quad \text{for all } j \in J, h \in H, d \in D \quad (45)$$

$$\sum_{l \in L} Q_{ikl}^d \leq (X_k - \sum_{f \in F} X_{kf})(1 - \alpha_k^d) \text{cap}_{ik} \quad \text{for all } i \in I, k \in K, d \in D \quad (46)$$

$$\sum_{j \in J} \sum_{l \in L} v_j Q_{jlr}^d \leq \text{cap}_r X_r \quad \text{for all } r \in R, d \in D \quad (47)$$

$$\sum_{l \in L} Q_{fikl}^d \leq \text{cap}_{ik} \sum_{f \in F} X_{kf} (1 - \beta_{kf}^d) \quad \text{for all } i \in I, k \in K, d \in D \quad (48)$$

$$X_k, X_l, X_r, X_{kf}, X_{bk} \in \{0,1\} \quad \text{for all } k \in K, l \in L, r \in R, f \in F \quad (49)$$

$$Q_{jl}^d, Q_{ikl}^d, Q_{fikl}^d, Q_{bikl}^d, Q_{jlr}^d, Q_{jrh}^d, Q_{lsh}^d \geq 0 \quad \text{for all } j \in J, i \in I, k \in K, l \in L, r \in R, h \in H, d \in D \quad (50)$$

Step 8: Solving the model.

The equivalent multi-objective model is turned into a single objective model using the ϵ -constraint method, a method providing a set of Pareto solution to decision-makers and allowing them to select the most appropriate solution depending on their preferences (Pishvae and Razmi, 2012: 3440).

Suppose the following multi-objective mathematical modelling problem:

$$\max (f_1(x), f_2(x), \dots, f_p(x)) \quad (51)$$

Subject to:

$$x \in S$$

where p objective functions are indicated by $f_1(x), \dots, f_p(x)$, decision variables' vector and the feasible region are denoted by x and S, respectively. In the ϵ -constraint method, among the objective functions, one is optimized by using the others as constraints limited to ϵ values in addition to the other constraints in the model as given below (Mavrotas, 2009: 456):

$$\max f_1(x) \quad (52)$$

Subject to:

$$f_2(x) \geq \epsilon_2$$

$$f_3(x) \geq \epsilon_3$$

...

$$f_p(x) \geq \epsilon_p$$

$$x \in S$$

In the model proposed in this study, the first objective function, implying the minimization of total cost, is hold as the objective function. The equivalent formula (Z) is as follows (Mohammed et al., 2019b: 303):

$$\text{Min } Z = \text{Min } Z_1 \quad (53)$$

Subject to:

$$Z_2 \geq \epsilon_1 \quad (54)$$

$$[Z_2]^{min} \leq \epsilon_1 \leq [Z_2]^{max} \quad (55)$$

In addition to Eqs. (32) - (50).

The second objective function refers to the maximization of suppliers' scores is treated as a constraint that its value can change between the minimum and maximum achievable supplier scores.

4. APPLICATION OF THE PROPOSED METHODOLOGY

A hypothetical problem is created to apply the proposed methodology. The manufacturer, the focal company in the problem, needs to supply 3 types of raw materials to produce 4 types of products. It formed a candidate supplier list for the selection of primary suppliers, including 11 suppliers that can be classified under 4 clusters based on

their closeness to each other. These clusters are as follows: K1-K2-K3 (1st cluster), K4-K5-K6 (2nd cluster), K7-K8-K9 (3rd cluster), and K10-K11 (4th cluster). A disruption in a cluster may affect multiple suppliers in that cluster. Those suppliers have different supply capacities and sales prices. To cope with the probable disruptions that may affect the capacity of suppliers, supplier fortification, and backup supplier usage strategies are considered. All suppliers can be fortified at three levels, each at a different cost, to reduce their capacity losses in case of disruption. A candidate backup supplier list is created based on the locations and resilience levels of the suppliers taken place in the primary supplier list to apply the backup supplier usage strategy. The suppliers included in the primary supplier candidate list considered not to be affected by the disruption scenarios are constituted in the candidate backup supplier list. If a supplier is selected as a backup supplier, its raw material supply capacity will be one-third of the capacity that it is chosen as a primary supplier. Contracting costs arise for each selected backup supplier.

The focal company has 4 manufacturing facility alternatives with different production capacities, establishment costs, and locations; and also 3 DCs to transfer its products to 3 market zones. DCs have different storage capacities and establishment and transportation costs. The objective is to create a supply network structure considering the minimization of the total cost, including costs of supplier selection, the establishment of manufacturing facilities and distribution centers, purchasing raw materials, all transportations in the network, and maximization of supplier scores.

The literature has been reviewed deeply, focusing on the recent studies addressing resilience in the context of the supply chain to evaluate the candidate suppliers. As a result, it has been decided to evaluate suppliers under the main criteria of primary, sustainability and resilience, and various sub-criteria. In Figure 4, the hierarchical structure of the selected main criteria and sub-criteria are presented.

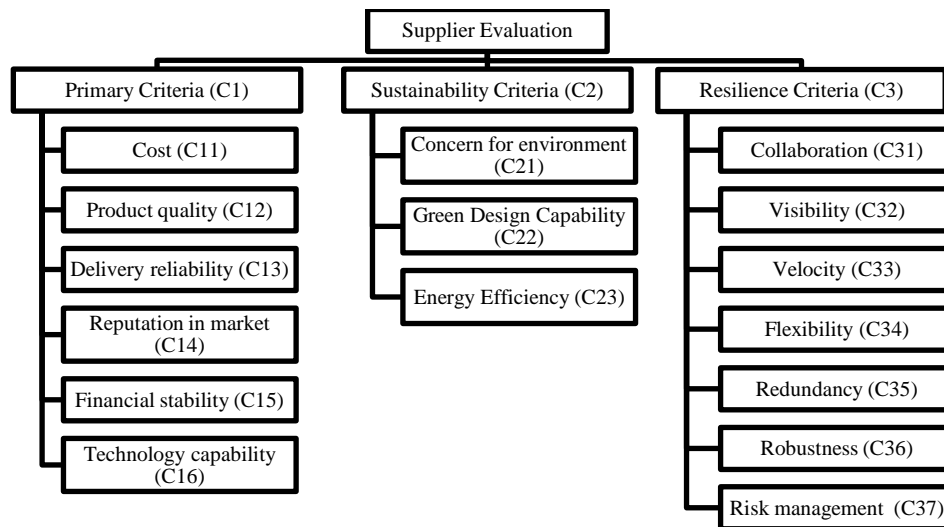


Figure 4. Hierarchical Structure of the Supplier Evaluation Criteria

The decision-making group consists of three senior managers. Fuzzy pairwise comparison matrices are constructed to calculate relative importance weights of criteria and priority weights of suppliers. Among them, pairwise comparison matrices among the main criteria, sub-criteria of primary supplier evaluation criteria, and alternative suppliers under criteria C11 by decision-maker 1 (DM1) are given in Table 3 -5 as examples.

Table 3. Fuzzy Pairwise Comparison Matrix among the Main Criteria

Criteria	DM1			DM2			DM3		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
C1	1	$\bar{3}$	$\bar{3}$	1	$\bar{3}$	$\bar{3}$	1	$\bar{3}$	$\bar{1}$
C2	$1/\bar{3}$	1	$1/\bar{1}$	$1/\bar{3}$	1	$1/\bar{1}$	$1/\bar{3}$	1	$1/\bar{3}$
C3	$1/\bar{3}$	$\bar{1}$	1	$1/\bar{3}$	$\bar{1}$	1	$1/\bar{1}$	$\bar{3}$	1

Table 4. Fuzzy Pairwise Comparison Matrix among Sub-Criteria of Primary Supplier Evaluation Criteria

Criteria	DM1						DM2						DM3					
	C11	C12	C13	C14	C15	C16	C11	C12	C13	C14	C15	C16	C11	C12	C13	C14	C15	C16
C11	1	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	1	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	$\tilde{3}$	1	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$
C12	$1/\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$1/\tilde{1}$	1	$\tilde{5}$	$\tilde{3}$	$\tilde{1}$	$\tilde{3}$	$1/\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$
C13	$1/\tilde{3}$	$1/\tilde{1}$	1	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{5}$	1	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{1}$	1	$1/\tilde{1}$	$1/\tilde{1}$	$1/\tilde{1}$
C14	$1/\tilde{3}$	$1/\tilde{1}$	$\tilde{1}$	1	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	$\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{1}$	$\tilde{1}$	1	$\tilde{1}$	$\tilde{1}$
C15	$1/\tilde{3}$	$1/\tilde{1}$	$1/\tilde{1}$	$\tilde{1}$	1	$1/\tilde{1}$	$1/\tilde{1}$	$1/\tilde{1}$	$\tilde{3}$	$1/\tilde{1}$	1	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{1}$	1	$\tilde{1}$
C16	$1/\tilde{3}$	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{1}$	$\tilde{1}$	1	$1/\tilde{3}$	$1/\tilde{3}$	$\tilde{3}$	$1/\tilde{1}$	$1/\tilde{1}$	1	$1/\tilde{3}$	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{1}$	$1/\tilde{1}$	1

Table 5. Fuzzy Pairwise Comparison Matrix of Alternative Suppliers under Criteria C11 by DM1

C11 Alternatives	DM1										
	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11
K1	1	$1/\tilde{3}$	$\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{1}$	$1/\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{1}$
K2	$\tilde{3}$	1	$\tilde{3}$	$\tilde{3}$	$1/\tilde{3}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$
K3	$1/\tilde{1}$	$1/\tilde{3}$	1	$1/\tilde{1}$	$1/\tilde{5}$	$1/\tilde{3}$	$\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{1}$
K4	$\tilde{1}$	$1/\tilde{3}$	$\tilde{1}$	1	$1/\tilde{5}$	$1/\tilde{1}$	$\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{1}$
K5	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	1	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$
K6	$\tilde{1}$	$1/\tilde{1}$	$\tilde{3}$	$\tilde{1}$	$1/\tilde{1}$	1	$\tilde{3}$	$\tilde{1}$	$1/\tilde{1}$	$\tilde{1}$	$\tilde{3}$
K7	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	1	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{1}$
K8	$\tilde{1}$	$1/\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$1/\tilde{5}$	$1/\tilde{1}$	$\tilde{1}$	1	$1/\tilde{3}$	$1/\tilde{3}$	$\tilde{1}$
K9	$\tilde{3}$	$1/\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$1/\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	1	$\tilde{1}$	$\tilde{3}$
K10	$\tilde{3}$	$1/\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$1/\tilde{3}$	$1/\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$1/\tilde{1}$	1	$\tilde{1}$
K11	$\tilde{1}$	$1/\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$1/\tilde{5}$	$1/\tilde{3}$	$\tilde{1}$	$1/\tilde{1}$	$1/\tilde{3}$	$1/\tilde{1}$	1

After preparation of all pairwise comparison matrices containing individual evaluations of decision-makers, aggregated fuzzy pairwise comparison matrices are created by following Step 3 in the methodology section. Aggregated fuzzy pairwise comparison matrix for the main criteria is given in Table 6 as a sample calculation to explain how to aggregate decision-makers' evaluations.

Table 6: Aggregated Pairwise Comparison Matrix for the Main Criteria

Criteria	C1			C2			C3		
	l	m	u	l	m	u	l	m	u
C1	1	1	2	2	3	4	1.587	2.080	3.175
C2	0.250	0.333	0.500	1	1	2	0.397	0.693	0.794
C3	0.315	0.481	0.630	1.260	1.442	2.520	1	1	2

In this matrix, three experts' pairwise comparisons of C1 and C3 in fuzzy numbers are as $\tilde{3}$ (2,3,4), $\tilde{3}$ (2,3,4) and $\tilde{1}$ (1,1,2). The aggregated evaluations of the decision makers have been calculated as follows:

$$n^- = (2 \times 2 \times 1)^{1/3} = 1.587$$

$$n = (3 \times 3 \times 1)^{1/3} = 2.080$$

$$n^+ = (4 \times 4 \times 2)^{1/3} = 3.175$$

Following the next steps of the F-AHP implementation process, crisp relative importance weights of the criteria and priority weights of the suppliers are obtained, as in Table 7-8.

Table 7. Crisp Relative Importance Weights of the Criteria

Main Criteria	Sub Criteria	Local weights	Global weights	Main Criteria	Sub Criteria	Local weights	Global weights
C1			0.566	C3			0.300
	C11	0.381	0.215		C31	0.359	0.108
	C12	0.217	0.123		C32	0.122	0.037
	C13	0.04	0.023		C33	0.061	0.018
	C14	0.136	0.077		C34	0.321	0.096
	C15	0.103	0.058		C35	0.053	0.016
	C16	0.123	0.07		C36	0.028	0.008
C2			0.134		C37	0.056	0.017
	C21	0.333	0.045				
	C22	0.333	0.045				
	C23	0.333	0.045				

The F-AHP results imply that the most important main supplier evaluation criterion is the primary criterion with a global weight of 0.566. Following the primary criterion, resilience is the second important main criterion with a 0.300 global weight. The most important sub-criteria are C11 (cost), C12 (product quality), C31 (collaboration) and C34 (flexibility) with global weights of 0.215, 0.123, 0.108 and 0.096, respectively. The priority weights of the suppliers are given in Table 7.

In the overall evaluation, suppliers with the highest score (those with priority weights > 0.10) are K4, K3, K1, K10, K7, respectively. When the rankings based on the main criteria are examined, K2, K10, K9, and K5 are the top ones according to the primary criteria, and K8 is the worst; on the resilience side, K7, K4, K1, K3, and K10 are the ones having the highest resilience score and K8 is the worst again. Sustainability scores of suppliers are parallel with their resilience scores.

Table 8. Priority Weights of the Suppliers

	Primary (C1)	Sustainability (C2)	Resilience (C3)	Priority weights	Rank
Criteria weights	0.566	0.134	0.300		
K1	0.089	0.152	0.146	0.115	3
K2	0.119	0.037	0.052	0.088	7
K3	0.098	0.148	0.138	0.117	2
K4	0.097	0.144	0.150	0.119	1
K5	0.105	0.047	0.029	0.074	8
K6	0.088	0.038	0.038	0.067	10
K7	0.067	0.151	0.152	0.104	5
K8	0.041	0.038	0.025	0.036	11
K9	0.105	0.089	0.074	0.094	6
K10	0.118	0.091	0.116	0.114	4
K11	0.072	0.064	0.080	0.073	9

After obtaining the suppliers' priority weights, the developed multi-objective mathematical model is solved firstly without allowing the application of fortification and backup supplier usage strategies, under no disruption state. Afterward, these strategies are first allowed to be applied individually, then simultaneously. The maximum number of primary suppliers permitted to be selected is set as 8.

In model data preparation, fuzzy parameters are transformed into certain values by applying the weighted average method with the weights, and β explained in Step 7. As an example, the calculation of crisp forecasted demand values is presented as follows:

$$d_{11} = \frac{d_{11}^p + 4d_{11}^m + d_{11}^o}{6}$$

$$d_{11} = \frac{150,000 + 4(200,000) + 250,000}{6}$$

$$d_{11} = 200,000 \text{ unit}$$

Crisp value of product type 1's demand of market zone 1 (d_{11}) is calculated by weighing the decision-makers' the most pessimistic (d_{11}^p), the most likely (d_{11}^m) and the most optimistic (d_{11}^o) evaluations regarding that demand by using the weights of 1/6, 4/6, and 1/6 and β as 0.5. As a result, d_{11} is obtained as 200,000 unit.

The evaluations and calculated demand data are presented in Tables 9-10. All model inputs' value ranges are given in Table 11.

Table 9. The Most Pessimistic (p), the Most Likely (m), and the Most Optimistic (o) Demand Values

Product Types	Market Zones								
	h=1			h=2			h=3		
	d_{jh}^p	d_{jh}^m	d_{jh}^o	d_{jh}^p	d_{jh}^m	d_{jh}^o	d_{jh}^p	d_{jh}^m	d_{jh}^o
j=1	150,000	200,000	250,000	112,500	150,000	187,500	67,500	90,000	112,500
j=2	93,750	125,000	156,250	135,000	180,000	225,000	56,250	75,000	93,750
j=3	37,500	50,000	62,500	150,000	200,000	250,000	150,000	200,000	250,000
j=4	67,500	90,000	112,500	75,000	100,000	125,000	93,750	125,000	156,250

Table 10. Crisp Demand Values (d_{jh})

Product Types	Market Zones		
	h=1	h=2	h=3
j=1	200,000	150,000	90,000
j=2	125,000	180,000	75,000
j=3	50,000	200,000	200,000
j=4	90,000	100,000	125,000

Table 11. Value Ranges of Model Inputs

Parameters	Value Ranges	Parameters	Value Ranges																				
fc_k	48,000 – 72,000	pt_{ji}	0.003 - 0.007																				
fb_k	33,000 – 36,000	cp_{ikl}	1.480 – 6.260																				
fc_{kf}	15,000 - 43,800 / 31,500 - 78,900 / 40,500 - 96,900	ct_{jlr}	0.002 – 0.092																				
fc_i	575,000 – 64,000	ct_{jrh}	0.009 – 0.098																				
fc_r	151,000 - 158,000	cls_{jh}	70 -135																				
cap_i	1,901.250 – 2,925	d_{jh}	50,000 – 200,000																				
cap_r	56,250 – 75,000	q_{ij}	<table border="1" style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th></th> <th>j_1</th> <th>j_2</th> <th>j_3</th> <th>j_4</th> </tr> </thead> <tbody> <tr> <td>i_1</td> <td>2</td> <td>1</td> <td>2</td> <td>4</td> </tr> <tr> <td>i_2</td> <td>1</td> <td>1</td> <td>2</td> <td>2</td> </tr> <tr> <td>i_3</td> <td>2</td> <td>2</td> <td>1</td> <td>2</td> </tr> </tbody> </table>		j_1	j_2	j_3	j_4	i_1	2	1	2	4	i_2	1	1	2	2	i_3	2	2	1	2
	j_1	j_2	j_3	j_4																			
i_1	2	1	2	4																			
i_2	1	1	2	2																			
i_3	2	2	1	2																			
v_j	0.024 – 0.065	cap_{ik}	120,000 – 960,000																				
cp_{jl}	10 – 32.500	cap_{bk}	40,000 – 280,000																				

Resilient supply chain networks must be capable of coping with situations that may significantly disrupt suppliers. A total of 8 disruption scenarios that have significant capacity reductions on suppliers were derived to make the supply chain network addressed in this study that capable. In the derivation process, both the resilience and locations of suppliers were considered. In 5 of these scenarios, only one supplier is affected, while in 3, two suppliers are influenced simultaneously. Suppliers 4-5-6 and 7-8 are located in areas close to each other, and the risk of disruption is high. Suppliers 7 and 4 are the suppliers with the most top resilience scores, but they have been included in the disruption scenarios due to their locations. Suppliers that are not affected by derived disruption scenarios and have a high resilience score, K1, K3, K7, and K10 are included in the candidate backup suppliers list.

All details regarding the derived scenarios are given in Table 12. The first scenario (d1) with 0.14 probability of occurrence indicates that only supplier K2 will be affected by this disruption, and 0.75 capacity decrease will occur in this supplier. If this supplier is chosen to be fortified, the capacity decrease will be 0.675, with the lowest fortification level and 0.225 with the highest fortification level. The eighth scenario (d8), one of the scenarios having impacts on two suppliers simultaneously, has 0.08 occurrence probability and will affect K7 and K8 with a 0.90 capacity decrease. If the fortification strategy is applied to K7 and K8, this decrease will be 0.65 and 0.81 at the lowest fortification level and 0.15 and 0.27 at the highest fortification level, respectively.

Table 12. Derived Disruption Scenarios' Data

Scenarios	Probability of occurrence	Supplier(s) effected	Capacity reduction percentage	Capacity reduction in case of fortification strategy applied		
				f=1	f=2	f=3
d=1	0.14	K2	0.75	0.675	0.525	0.225
d=2	0.15	K5	0.83	0.747	0.581	0.249
d=3	0.12	K6	0.82	0.738	0.574	0.246
d=4	0.13	K8	0.85	0.765	0.595	0.255
d=5	0.16	K11	0.73	0.657	0.511	0.219
d=6	0.15	K4 and K5	0.85	0.765	0.595	0.255
d=7	0.08	K4 and K6	each one 0.85	each one 0.765	each one 0.595	each one 0.255
d=8	0.07	K7 and K8	each one 0.90	each one 0.65 K7 0.81 K8	each one 0.35 K7 0.63 K8	each one 0.15 K7 0.27 K8

The model, with its all variants, is solved to maximize and minimize the objective functions individually with LINGO software. The model is also solved under 10% demand raises in addition to expected demand conditions to evaluate the impact of demand increases on the supply network decisions. The minimum and maximum objective function values obtained optimization of each objective individually are given in Table 13.

Table 13. Values of Each Objective Function under Expected Demand and 10% Increased Demand

Obj.Func.	Expected Demand				Increased expected demand by 10%			
	ND	F	B	F&B	ND	F	B	F&B
Max Z1	66,216,680	66,719,860	66,021,930	66,791,680	71,920,800	72,390,710	71,455,510	72,480,760
Min Z1	54,297,330	54,768,750	54,826,350	54,768,750	60,261,150	60,740,240	61,044,090	60,721,840
Max Z2	0.824	0.824	1	1	0.824	0.824	0.933	1
Min Z2	0.471	0.500	0.615	0.500	0.503	0.586	0.793	0.586

ND: No disruption & no supplier strategy, F: Allowing only fortification of suppliers strategy under disruption scenarios, B: Allowing only backup supplier usage strategy under disruption scenarios, F&B: Allowing fortification of suppliers and backup supplier usage strategies simultaneously under disruption scenarios

The minimum total cost is achieved under no-disruption for all considered demand conditions. Under disruption scenarios for expected demand situation, the strategies of F, and F&B provide the minimum total costs. It means not using any backup suppliers, only applying fortification of selected suppliers at the chosen levels, the minimum total cost is obtained. In the 10% demand increase case under disruption scenarios, the minimum total cost is reached by applying the F&B.

A pareto optimal solutions set is obtained using the objective of minimization of the total cost (Z1) as the objective function and maximization of total supplier score (Z2) as a constraint in the model under disruption scenarios. Lower bound of total supplier score value is set as the minimum Z2 value achieved in no-disruption case. Then, the model is solved repeatedly, starting from this value up to 1 by 0.10 supplier score increments. Pareto optimal solutions, total costs, total supplier scores, selected suppliers as primary and backup suppliers, and to be fortified at different levels, opened manufacturing facilities, and DCS are presented in Table 14.

Table 14. Pareto Optimal Solutions – Expected Demand & 10% Demand Increase

Demand Condition	Supplier Score Constraint	Total Cost	Supplier Score	Selected Primary Suppliers	Selected Backup Suppliers	Fortified Suppliers	Opened Manuf. Facilities	Opened DCs
Expected Demand	$\sum_{k \in K} s_k X_k \geq 0.471$	54,768,750	0.665	K2-K4-K5-K6-K8-K9- K10- K11	-	K4 at level 1 / K6 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.500$	54,768,750	0.665	K2-K4-K5-K6-K8-K9- K10- K11	-	K4 at level 1 / K6 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.600$	54,768,750	0.665	K2-K4-K5-K6-K8-K9-K10-K11	-	K4 at level 1 / K6 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.700$	54,780,520	0.764	K2-K5-K6-K7-K8-K9-K10-K11	K1	K6 at level 3 / K7 at level 1	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.800$	54,813,190	0.881	K2-K5-K6-K7-K8-K9-K10-K11	K1- K3	K6 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.900$	54,857,470	1	K2-K4-K5-K6-K8-K9-K10-K11	K1-K3- K7	K6 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 1$	54,857,470	1	K2-K4-K5-K6-K8-K9-K10- K11	K1- K3-K7	K6 at level 3	11-14	DC 2
10% Demand Increase	$\sum_{k \in K} s_k X_k \geq 0.503$	60,721,840	0.764	K2-K5-K6-K7-K8-K9-K10- K11	K1	K6 at level 3 / K7 at level 3 / K11 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.600$	60,721,840	0.764	K2-K5-K6-K7-K8-K9-K10- K11	K1	K6 at level 3 / K7 at level 3 / K11 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.700$	60,721,840	0.764	K2-K5-K6-K7-K8-K9-K10- K11	K1	K6 at level 3 / K7 at level 3 / K11 at level 3	11-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.800$	60,777,740	0.881	K2-K5-K6-K7-K8-K9-K10-K11	K1-K3	K6 at level 3 / K7 at level 3 / K11 at level 3	11-13-14	DC 2
	$\sum_{k \in K} s_k X_k \geq 0.900$	60,946,230	1	K2-K4-K5-K6-K8-K9-K10- K11	K1- K3-K7	K6 at level 3	11-13-14	DC 1
$\sum_{k \in K} s_k X_k \geq 1$	60,946,230	1	K2-K4-K5-K6-K8-K9-K10-K11	K1-K3-K7	K6 at level 3	11-13-14	DC 1	

In the pareto optimal solution set for the expected demand case, until the lower boundary of the supplier score is 0.7, only suppliers' fortification strategy is chosen to be applied. Fortified suppliers are K4 with level 1 and K6 with level 3. Above this bound of supplier score, suppliers' fortification and backup supplier usage strategies are simultaneously applied.

In the 10% demand increase case, suppliers' fortification and backup supplier usage strategies are simultaneously applied in all supplier score conditions.

5. CONCLUSION AND FURTHER RESEARCH

The SCND problem that has been studied in the literature for many years has recently been addressed by considering the resilience dimension. Current global supply chain networks may include chain members located in different geographical locations and at different readiness levels to cope with disruptions. At this point, the competitiveness of companies is inevitably affected by how the supply chain network that they are involved in reacts in case of any supply chain disruptions and how long it turns to a stable state. From this point of view, in this study, a resilient SCND problem that has received a great deal of attention in the literature recently is addressed. The concept of supply chain resilience, its dimensions, and strategies that have mentioned in the literature are provided throughout the study. An integrated two-step fuzzy approach is proposed to analyze the resilient SCND problem. The first step of the approach includes the evaluation of the candidate suppliers under multi-criteria and obtaining their overall scores by applying the F-AHP. Supplier evaluation criteria are determined as primary, sustainability, and resilience criteria based on the review of the studies that have addressed the resilience concept in the supply chain focus. In the second step, the supply chain network is constructed with the minimization of total costs related to the network structure and maximization of the overall supplier score objectives. In the calculation of overall supplier score, aggregated scores of suppliers under primary, sustainability, and resilience criteria have been used. It is aimed to select suppliers as both primary and backup in a way that

maximizes total supplier score. An F-MLP model is proposed to obtain the network structure in which suppliers to be selected, manufacturing facilities, and DCs to be opened determined. The model is solved with the ϵ -constraint method under various derived disruption scenarios with different occurrence probabilities and impact sizes by considering the resilience strategies of fortification of suppliers and having backup suppliers both individually and simultaneously for a hypothetical problem. The minimization of total cost objective is held as the objective function, while the maximization of total supplier scores is used as a constraint, and the pareto optimal solution set is created. The F&B strategy, applying both strategies of fortification of suppliers and using backup suppliers, provided the minimum total cost in almost all supplier score conditions of pareto optimal solution set. The decision-makers can select solutions from this set that presents different total costs and supplier scores based on their preferences.

The methodology proposed in this study considers only the supply side's resilience; only some of the suppliers' production capacities are affected in the derived disruption scenarios, and only resilience strategies related to suppliers are applied. In further studies, resilience can be handled for the other chain members with the same methodology. Disruption scenarios that may affect manufacturing facilities and DCs can be derived, and resilience strategies for these members, such as fortification of facilities and capacity expansion, can be applied. Also, the maximization of the overall supplier score objective function in the mathematical model can be expressed in different ways. Overall supplier scores can be calculated by weighing the individual supplier scores with the amount of raw material to be provided from that supplier and instead of using aggregated supplier scores and one objective function to maximize overall supplier scores, objective functions to maximize primary, sustainability and resilience scores of suppliers separately can be utilized.

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