WORKING PAPER

ITLS-WP-17-20

Sustainability Analysis under Disruption Risks

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November 2017

ISSN 1832-570X

INSTITUTE of TRANSPORT and LOGISTICS STUDIES

The Australian Key Centre in Transport and Logistics Management

The University of Sydney

Established under the Australian Research Council's Key Centre Program.

NUMBER:	Working Paper ITLS-WP-17-20
TITLE:	**Sustainability Analysis under Disruption Risks**
ABSTRACT:	Resilience to disruptions and sustainability are both of paramount importance to supply chains. This paper presents a hybrid methodology for the design of a sustainable supply network that performs resiliently in the face of random disruptions. A stochastic bi-objective optimization model is developed that utilizes a fuzzy c-means clustering method to quantify and assess the sustainability performance of the suppliers. The proposed model determines outsourcing decisions and buttressing strategies that minimize the expected total cost and maximize the overall sustainability performance in disruptions. Important managerial insights and practical implications are obtained from the model implementation in a case study of plastic pipe industry.
KEY WORDS:	***Supply Chain Management; Resilience; Disruption; Sustainability; Optimisation***
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DATE:	November 2017

1. Introduction

The modern global economy has developed interconnected and complex supply chains. This is in large part due to the benefits companies have found in sophisticated trends and strategies such as globalization, outsourcing, supply-base rationalization, just-in-time deliveries, and lean practices (Hasani and Khosrojerdi, 2016; Rezapour et al., 2014). Whilst these practices have led to lower costs, higher quality, and enhanced business agility for many supply chains, they are not without risk (Tang, 2006b). As supply chains grow more complex, they become more vulnerable to disruptions caused by various means such as natural disasters, political unrest, strikes, unexpected regulatory issues, port problems, and terrorist activities (Snyder et al., 2016). Firms with global supply chains, for instance, face more potential points of failure caused by global customs, foreign regulations and port congestion, and political and/or economic instability in a source country (Kouvelis et al., 2011). Likewise, lean inventories and just-in-time processes undermine the supply chains' abilities to withstand supply disruptions by leaving little room for error when situations change drastically (Peng et al., 2011).

Past and recent disasters have demonstrated the dramatic consequences of unexpected disruptions on supply chains such as production shutdowns, hampered productivity and capacity utilization (Cardoso et al., 2015; Jabbarzadeh et al., 2015). In the longer term, such consequences can negatively impact share/stuck prices and the long-term financial health of the company (Hendricks and Singhal, 2005; Tang, 2006a). Hurricanes Katrina, Ike, Sandy and Mathew, in United States (2005, 2008 and 2012) and Atlantic Coast (2016), tsunamis in the Indian Ocean (2004) and Japan (2011), earthquakes in China (2008) and Chile (2011 and 2015), and flood in the Philippines (2013) are recent examples of these devastating events (Jabbarzadeh et al., 2016). Realizing the negative impacts of disruptions, companies more than ever attempt to create and be part of more resilient supply chains (Baghalian et al., 2013; Tomlin, 2006). A resilient supply chain is able to absorb disturbances and retain its basic function and structure in the face of disruptions (Bhamra et al., 2011; Christopher and Peck, 2004; Jabbarzadeh et al., 2016).

The resilience of a supply chain is highly dependent on its structure/design. That is, companies with carefully designed supply chains are typically more resilient to disruption risks (Dixit et al., 2016; Jabbarzadeh et al., 2014; Klibi et al., 2010; Zokaee et al., 2014). As a result, resilient design of a supply chain has consistently drawn the attention of practitioners and researchers in recent years. However, the research efforts have predominantly focused on minimizing the total supply chain costs in normal and disruption situations, disregarding the environmental and social performance of the supply chain. In other words, maintaining the economic sustainability has been the primary focus of the existing research, whilst the impact of risk mitigation methods on the environmental and social performance of the supply chain have been rarely examined, especially at the strategic supply chain design level

(Fahimnia and Jabbarzadeh, 2016). Given that sustainable development has been an integral part of virtually every business in today's world, this calls for management approaches that are able to concurrently incorporate the three dimensions of sustainability (i.e., economic, environmental and social) when designing resilient supply chains (Fahimnia et al., 2015d; Hassini et al., 2012; Seuring, 2013). The necessity for such approaches would be more pronounced when the three sustainability dimensions are conflicting and some trade-offs may be required (Matthew and Hammill, 2009).

To respond to this call, this paper presents a two-phase approach for designing sustainable supply chain networks that are resilient to disruptions. The first phase of this approach identifies, quantifies and aggregates the sustainability performance measures using a fuzzy clustering approach named *fuzzy c-means clustering* method. Using the obtained scores of sustainability, the second phase adopts a stochastic bi-objective optimization model to determine the sourcing decisions (i.e., supplier selection and order allocation) and buttressing strategies (e.g., contracting with backup suppliers and adding extra production capacities to factories). The primary goal of the proposed model is to ensure that the sustainability performance of the supply chain remain unaffected in disruptions as much as practicable. An augmented ε-constraint method is used to convert the bi-objective model into a single objective formulation. The application of the proposed approach is examined using real data from an actual supply chain in plastic pipe industry.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature focusing on resilience and sustainability in supply chain design. Problem statement and the mathematical models are presented in Section 3. The case problem is examined in Section 4 followed by analyzing the numerical results and related discussions. Section 5 presents the concluding remarks as well as directions for future research in this space.

2. Review of the Relevant Literature

This section first reviews the modelling efforts in two areas of 'resilient supply chain design' and 'sustainable supply chain design'. This is then followed by discussing the nexus between the two topics and the associated research gaps.

2.1 Resilient supply chain design

The growing frequency of natural and man-made disasters (e.g., earthquakes, floods, terrorist attacks, strikes, etc.) and their devastating impacts on companies and their supply chains indicate the need to plan for resilience at the supply chain design level. The recent review of Snyder et al. (2016) shows that resilient supply chain design is an emerging research trend. The existing modeling efforts can be classified based on the buttressing (protecting) strategies that are used to enhance resilience against random disruptions. Common buttressing strategies include:

- multiple sourcing and assignment instead of single souring and assignment (e.g., (Allaoui et al., 2016); Kamalahmadi and Mellat-Parast (2016); Meena and Sarmah (2013); Nooraie and Parast (2016); Peng et al. (2011); Sadghiani et al. (2015); Sawik (2011a, 2013a, 2014a, b, 2016a, b, c); Torabi et al. (2016); Zhang et al. (2015));
- contracting with backup suppliers/facilities to serve when the primary suppliers/facilities are not available in disruptions (e.g., Aryanezhad et al. (2010); Fang et al. (2013); Hou et al. (2010); Jabbarzadeh et al. (2012); Shishebori et al. (2013); Snyder and Daskin (2005));
- fortification of suppliers/facilities to minimize their vulnerability to disruptions (e.g., Azad et al. (2013); Hasani and Khosrojerdi (2016); Jabbarzadeh et al. (2016); Li and Savachkin (2013); Li et al. (2013); Lim et al. (2010); Torabi et al. (2015));
- holding additional inventory to use in disruption situations (e.g., Garcia-Herreros et al. (2014); Sawik (2013b, c)); and
- adding extra supply/production capacities to cope with lost capacities of suppliers/factories in consequence of disruptions (e.g., Ivanov and Morozova (2016); Khalili et al. (2016)).

Amongst the aforementioned works, there are studies that focus on supplier selection and order allocation under supply disruption risks. Meena and Sarmah (2013) formulate a mixed integer non-linear programming model for determining order allocation considering different capacities, failure probabilities, and quantity discounts for each supplier. Kamalahmadi and Mellat-Parast (2016) examine an optimal allocation of demand across a set of suppliers in a supply chain that is exposed to supply risk and environmental risk. Their model integrates supplier selection and demand allocation with transportation channel selection and provides contingency plans to mitigate the negative impacts of disruptions and minimize total network costs. A scenario-based bi-objective possibilistic mixed integer linear model is presented by Torabi et al. (2015) to build resilient supply bases for global supply chains in response to disruption risks. The model applies several proactive strategies such as suppliers' business continuity plans and fortification of suppliers to enhance the resilience of the selected supply base.

Based on the two popular measures of value-at-risk (VaR) and conditional value-at-risk (CVaR), Sawik (2011a), Sawik (2011b), Sawik (2013c) and Sawik (2016c) present portfolio methodologies for managing supply disruption risks. Using the same approach, Sawik (2013a) and Sawik (2014a) propose stochastic mixed integer programming models to combine supplier selection, order quantity allocation and customer order scheduling in the presence of disruption risks. Sawik (2014b) and Sawik (2016b) enhance the earlier formulations by incorporating service level measures including the expected worst-case demand fulfillment rate and the expected worst-case order fulfillment rate. A non-linear robust optimization model is developed by Hasani and Khosrojerdi (2016) for designing robust global supply chains under the risk of correlated disruptions. The proposed model is solved for an electro-medical device manufacturer using a parallel Taguchi-based memetic algorithm. None of the above-cited works account for environmental and social aspects of sustainability.

2.2 Sustainable supply chain design

Supply chain sustainability has gained increased attention with a considerable growth in the number of academic publications over the past few years. For a comprehensive review of the literature in the area of sustainable and green supply chain management one can refer to Seuring and Müller (2008), Seuring (2013), Brandenburg et al. (2014), Srivastava (2007), and Fahimnia et al. (2015c). Also, Eskandarpour et al. (2015) and Igarashi et al. (2013) have completed literature reviews on sustainable supply chain network design and green supplier selection, respectively.

Supply chain sustainability seeks to incorporate environmental and social measures into the traditional cost-oriented supply chain management practices. The modelling approaches in the literature of green or environmentally sustainable supply chain design can be grouped into the following broad categories (Fahimnia and Jabbarzadeh, 2016; Seuring, 2013).

- Equilibrium models for balancing environmental and economic factors (Brandenburg, 2015; Cruz, 2008; Elhedhli and Merrick, 2012; Fahimnia et al., 2015d; Pishvaee and Razmi, 2012; Wang et al., 2011).
- Life-cycle assessment models focusing on the environmental concerns along supply chains and minimizing their impact (Bojarski et al., 2009; Ferretti et al., 2007; Hugo and Pistikopoulos, 2005).
- Optimization models for investigating environmental policy instruments such as carbon tax and trading mechanisms (Diabat et al., 2013; Fahimnia et al., 2015b; Zakeri et al., 2015).
- Closed-loop supply chain network design models addressing cost/emission performance of the forward and reverse networks (Chaabane et al., 2011, 2012; Fahimnia et al., 2013).

Compared with environmental dimension, the social side of sustainability has been less explored in the literature of supply chain design (Seuring and Müller, 2008). Whilst social sustainability can include various aspects of human rights (e.g., child and forced labor, freedom of association and discrimination) and business practice (e.g., fight against corruption, fair-trading, and promotion of corporate social responsibility in the sphere of influence), the modelling efforts have only tended to focus on some of the more tangible and quantifiable social dimensions such as (Chardine-Baumann and Botta-Genoulaz, 2014; Eskandarpour et al., 2015):

- work conditions (Boukherroub et al., 2015; Devika et al., 2014; Mota et al., 2015; Pérez-Fortes et al., 2012; Pishvaee et al., 2012; Santibañez-Aguilar et al., 2014);
- social commitment (Bouzembrak et al., 2013; Pishvaee et al., 2014; You et al., 2012); and
- costumer issue (Dehghanian and Mansour, 2009; Malczewski and Ogryczak, 1990; Zhang et al., 2014).

Apart from these studies, there is a handful of papers attempting to integrate economic, environmental and social dimensions of sustainability. Arampantzi and Minis (2017) propose a multi-objective mixed Integer linear programming model for designing a sustainable supply chain network. The environmental objective includes emission quantities and waste generation at each node/link of the supply chain, while the social objective reflects employment opportunities, societal community development and improved labor conditions. A two-stage solution methodology for supply chain design is presented by Allaoui et al. (2016) to simultaneously capture the three dimensions of sustainability including carbon footprint, water footprint, number of jobs created and the total cost of the supply chain. For a biodiesel supply chain design, Zhang and Jiang (2017) develop a multi-objective robust optimization model in which total carbon emissions and uncollected wastes are considered as environmental and social metrics, respectively.

2.3 Research gaps: resilient and sustainable supply chain design

Despite the rigorous modelling efforts in the two areas of resilient supply chain design and sustainable supply chain design, the joint consideration of sustainability and resilience has been a rare occurrence in the literature of supply chain design. Perhaps the works of Cabral et al. (2012), Azevedo et al. (2013) and Fahimnia and Jabbarzadeh (2016) are the most relevant to what we refer to as resilient and sustainable supply chain modelling. Cabral et al. (2012) propose a structured framework based on the analytic network process to integrate lean, agile, resilient and green paradigms in supply chains. Likewise, an integrated composite index, called the Ecosilient Index, is developed by Azevedo et al. (2013) to assess the greenness and resilience of companies and their supply chains. The application of the proposed index is illustrated using a case study from the automotive industry. The conceptual approaches proposed by Cabral et al. (2012) and Azevedo et al. (2013) overlook social sustainability aspects in supply chains.

Fahimnia and Jabbarzadeh (2016) investigate the sustainability-resilience relationship at the supply chain design level. A multi-objective optimization model is introduced that uses a sustainability performance scoring approach to quantify the environmental and social performance of the supply chain. To seek tradeoff solutions for developing a resilient and sustainable supply chain, a stochastic fuzzy goal programming approach is presented. While this study has set a solid stage for further work in this area, it comes with some modelling and implementation limitations that we wish to address in this current study. First, the model proposed by Fahimnia and Jabbarzadeh (2016) places no emphasis on production operations and purely concentrates on upstream supply chain activities (i.e. sourcing/procurement operations). Additionally, the developed model does not take into consideration the proactive buttressing strategies (such as adding extra supply/production capacities or contracting with backup suppliers) to protect the supply chain against disruptions.

Addressing these gaps, our study presents a simple but effective hybrid methodology that can be utilized to design a resilient and sustainable supply chain. Using the c-means fuzzy clustering technique, the proposed approach first assesses the suppliers' sustainability performance. In the next step, a bi-objective stochastic optimization model is utilized that aims to concurrently minimize expected total supply chain costs and maximize overall sustainability performance of the supply chain. The proposed model is capable of accounting for random disruptions by using various buttressing strategies to hedge against them. The application of the proposed methodology is examined in an empirical case study. Our analysis and discussions focus on exploring tradeoffs between total cost and sustainability performance as well as investigating the effectiveness of different buttressing strategies.

3. A Hybrid Approach for Resilient and Sustainable Supply Chain Design

The supply chain under investigation consists of suppliers, factories, and market zones, as depicted in Figure 1. Factories are served by a number of raw material suppliers whose economic, environmental and social performances may vary from one to another. Suppliers and factories are vulnerable to random disruptions. In other words, the capacities of suppliers and factories can be partially or completely impacted when a disruption occurs. A set of scenarios are defined to indicate situations in which one or more suppliers and facilities are influenced by disruptions. To hedge against disruption risks, three buttressing strategies are adopted: (1) utilizing multiple sourcing instead of single sourcing, (2) contracting with backup suppliers to serve factories when the primary suppliers are not available, and (3) adding extra production capacities to factories.

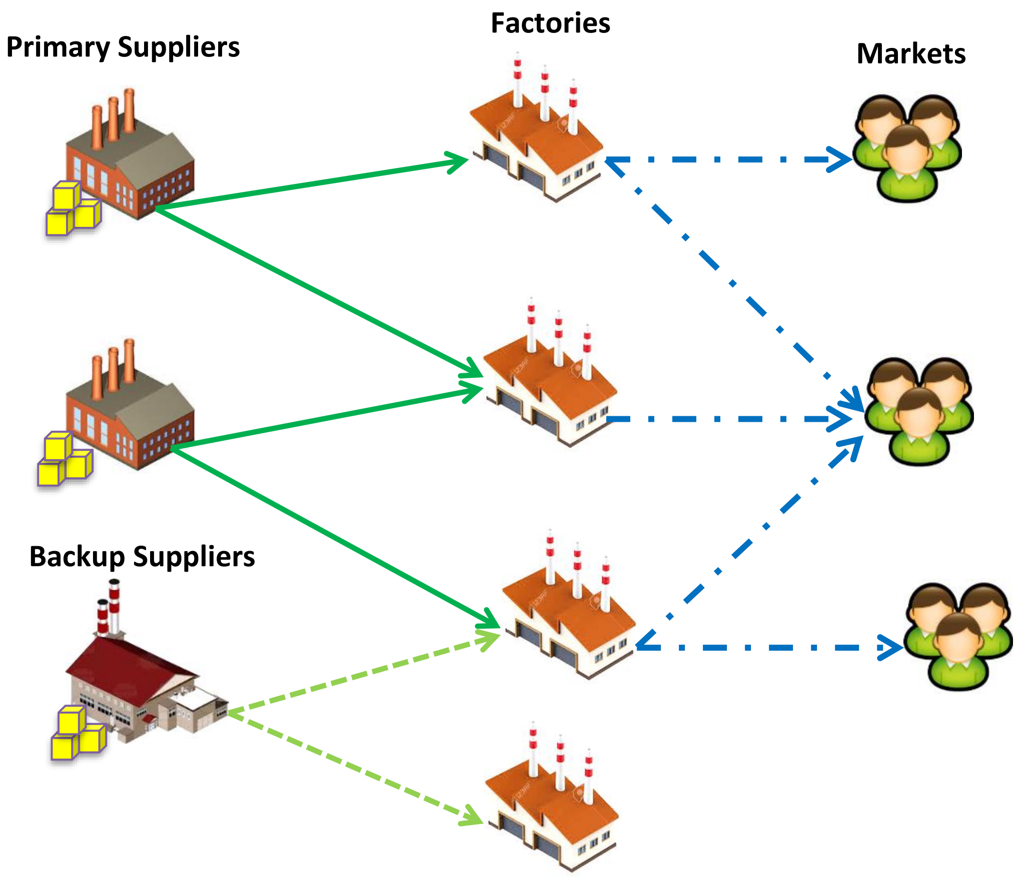


Figure 1. Structure of the supply chain under investigation

The problem lies in determining the following decisions:

- The selection of primary and backup suppliers,
- The amount of extra production capacity added to each factory,
- The quantity of raw material purchased from each supplier,
- The quantity of products manufactured in each factory,
- The quantity of products shipped from factories to market zones, and
- The quantity of lost sales at market zones.

To make the aforementioned decisions, a hybrid approach is used that aims to concurrently minimize the total expected cost and maximize the overall sustainability performance under random disruption scenarios. The proposed methodology involves two phases. The first phase assesses the sustainability performance of the potential suppliers based on a variety of economic, environmental, and social metrics. Applying *fuzzy c-means clustering* method, different sustainability measures are combined and the potential suppliers are split into different clusters with corresponding sustainability scores. The higher the score of each cluster, the more sustainable the suppliers' performance of that cluster. Based on the obtained scores, the set of suppliers with unsatisfactory scores are excluded from the potential suppliers.

In the second phase, a stochastic bi-objective model is developed in which the supplier's sustainability scores obtained from the first phase are incorporated as input parameters. The first objective is to minimize the expected total supply chain cost in different disruption scenarios, whilst the second objective aims at maximizing the expected aggregate weighted sustainability scores of all suppliers. The bi-objective model is converted into a single-objective model applying the augmented ε-constraint method. Figure 2 illustrates the steps of the two-phase algorithm. We elaborate each phase in the following sections.

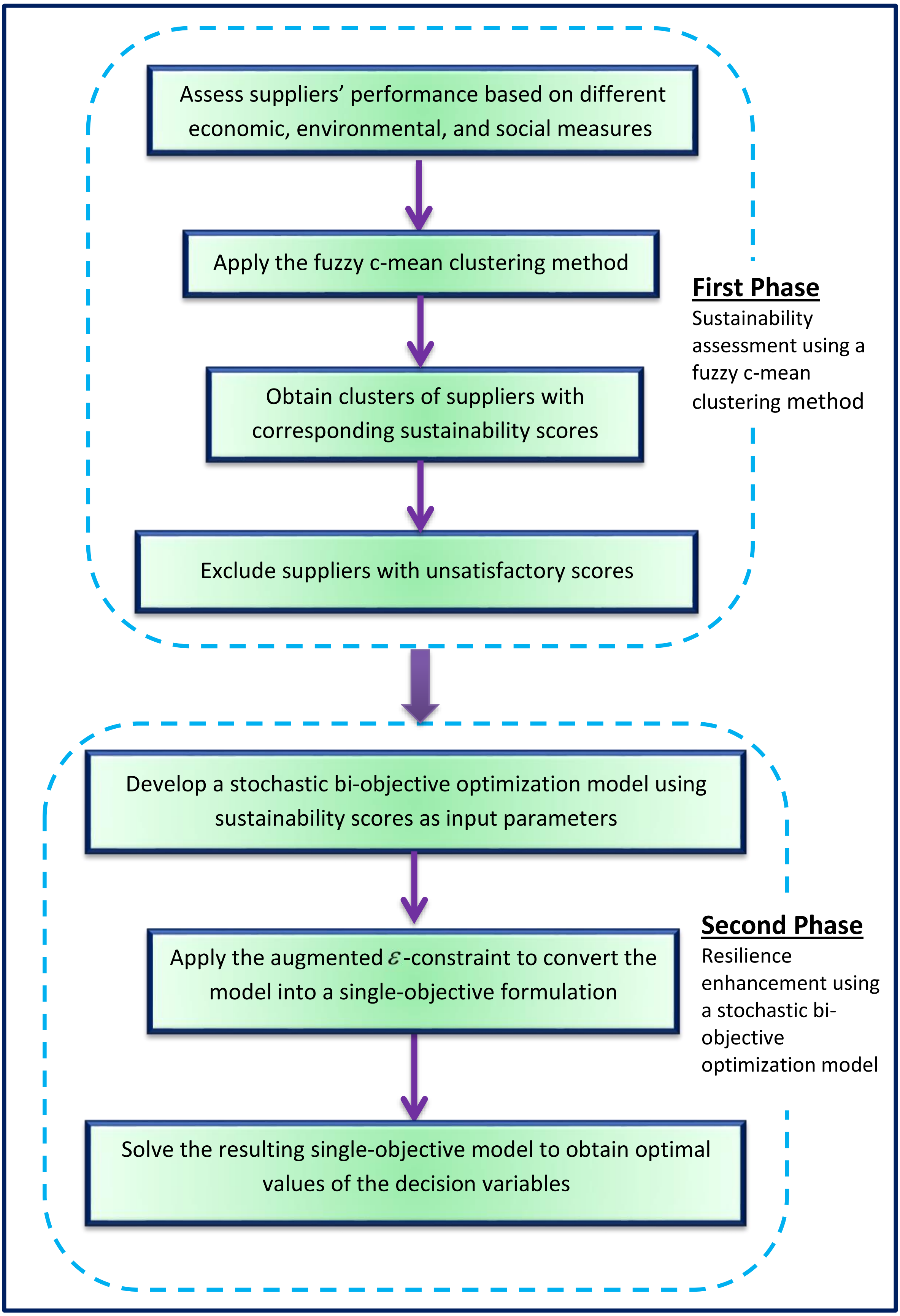


Figure 2. The steps of the proposed hybrid approach to design a resilient and sustainable supply chain

3.1 Sustainability assessment using a fuzzy c-means clustering method

As mentioned in the previous section, the first phase of our hybrid approach starts with assessing the economic, environmental and social performance of suppliers. For this purpose, the metrics defined by environmental impact assessment methods (e.g., IMPACT 2002+(Jolliet et al., 2003), Eco-indicator 99 (Goedkoop et al., 2009) and CML2001 (Guinée et al., 2001)) and social performance standards (e.g., SA8000 (SA, 2008), GRI (GRI, 2011), GSLCAP (Benoît, 2010)) can be adopted. Having assessed the performance of suppliers against each metric, the obtained results are aggregated using the fuzzy c-means clustering method, first introduced by Dunn (1973) and later enhanced by Bezdek et al. (1984). Using this approach, the suppliers are categorized into different clusters and a sustainability score is assigned to each supplier. The scores reflect the overall sustainability performance of suppliers in the way that a higher score indicates a more sustainable performance. Obtaining these scores, we can identify and exclude the suppliers with unsatisfactory sustainability performance.

Here, we describe the framework of the fuzzy c-means clustering method for clustering suppliers based on their sustainability performances. Let us assume we aim to partition n suppliers into o clusters (we will discuss at the end of this section how the value of o is selected). Additionally, let x_i be the vector reflecting the performance of supplier i based on the sustainability metrics. Now, the following steps are completed:

Step 1. Set identifier r equal to 1. Also, for each supplier and each cluster, generate a random value for membership degree of the supplier to the cluster. Let w_{ij} be the generated value for supplier i and cluster j indicating the degree to which supplier i belongs to cluster j.

Step 2. Calculate the center vector (c_j) for each cluster using the following equation:

$$c_j = \frac{\sum_{i=1}^{n} w_{ij}^{m} x^{i}}{\sum_{i=1}^{n} w_{ij}^{m}} \tag{1}$$

where the input parameter m takes a value larger than 1 and adjusts the fuzziness level of clusters. A larger value for m leads to smaller membership values, w_{ij}, and therefore, fuzzier clusters (Bezdek et al., 1984; Hathaway et al., 2000).

Step 3. Obtain the objective value of the fuzzy c-means clustering method (E^r) as follows:

$$E^r = \sum_{i=1}^{n}\sum_{j=1}^{o} w_{ij}{}^m \left\| x_i - c_j \right\|^2 \tag{2}$$

Step 4. Update the membership degrees as follows:

$$w_{ij} = \left(\sum_{k=1}^{c} \left(\frac{\left\| x_i - c_j \right\|}{\left\| x_i - c_k \right\|} \right)^{2/m-1} \right)^{-1} \tag{3}$$

Step 5. If $\left\| E^r - E^{r-1} \right\| \le \Delta$, then set $r = r + 1$ and go to step 2 (Δ is the error level set by the decision maker). Otherwise, go to step 6.

Step 6. Exclude the suppliers that belong to clusters with unsatisfactory sustainability performance.

Step 7. Return the sustainability score of remaining suppliers using the following equation:

$$\alpha_i = \sum_{j=1}^{o} w_{ij} \left\| c_j \right\| \tag{4}$$

Applying the method proposed by Rezaee et al. (1998), the number of clusters (o) is chosen in a way to minimize the following function , where $\bar{c}$ indicates the average measure for the center of clusters:

$$Min \sum_{i=1}^{n}\sum_{j=1}^{c} w_{ij}{}^m \left(\left\| x_i - c_j \right\|^2 - \left\| c_j - \bar{c} \right\|^2 \right) \tag{5}$$

3.2 Resilience enhancement using a stochastic bi-objective optimization model

The second phase of the hybrid algorithm develops a stochastic bi-objective optimization model in which the obtained suppliers' sustainability scores from the fuzzy c-means clustering method are incorporated as input parameters. The proposed model aims to determine decisions in a way that the designed supply chain remains resilient to disruptions at the lowest possible cost. Here, by supply chain resilience, we do not just mean viable cost performance but we also address desired environmental and social performance in disruption situations. Thus, accounting for different disruption scenarios, the developed model has two objective functions: 1) minimizing the expected total cost, and 2) maximizing the expected sustainability performance.

Applying the two-stage programming approach of Birge and Louveaux (2011), our model determines two types of decisions: first-stage and second-stage decisions. The first-stage decisions are made before realizing disruption scenarios and include determining the primary and backup suppliers selected to serve factories as well as the amounts of production capacities added to factories. The second-stage decisions are related to specific disruption scenarios and consist of determining the quantity of raw material purchased from each supplier, the quantity of products manufactured in each factory, the quantity of products shipped from factories to market zones, and the quantity of lost sales at market zones.

The following sets, parameters and decision variables are introduced for mathematical modeling of the problem.

Sets and indices:

R	Set of raw material types, indexed by r
N	Set of primary suppliers, indexed by n
L	Set of backup suppliers, indexed by l
M	Set of factories, indexed by m
J	Set of market zones, indexed by j
S	Set of disruption scenarios, indexed by s

Input parameters:

d_j	Forecasted demand in market zone j
h_r	Amount of raw material type r required for production of a unit final product
c_n	Initial supply capacity of primary supplier n
f_l	Initial supply capacity of backup supplier l
α_n	Sustainability score of primary supplier n obtained from the fuzzy c-means clustering method
β_l	Sustainability score of backup supplier l obtained from the fuzzy c-means clustering method
δ_{rn}	Defective rate of primary supplier n for raw material type r
γ_{rl}	Defective rate of backup supplier l for raw material type r
g_{ns}	Percentage supply capacity of primary supplier n disrupted under scenario s
x_n	Fixed cost of evaluating and selecting primary supplier n
z_l	Fixed cost of contracting with backup supplier l

q_{rnm}	Unit cost of purchasing raw material type r from primary supplier n and shipping it to factory m
u_{rlm}	Unit cost of purchasing raw material type r from backup supplier l and transporting it to factory m
w_m	Initial production capacity of factory m
k_m	Maximum extendable capacity of factory m
v_{ms}	Percentage production capacity of factory m disrupted under scenario s
p_m	Unit cost of manufacturing in factory m
e_m	The cost per unit for adding extra production capacity to factory m
y_{mj}	Unit cost of transportation from factory m to the market zone j
b_j	Unit cost of lost sales in market zone j
π_s	Possibility of occurrence of scenario s

Decision variables:

X_n	A binary variable, equal to 1 if primary supplier n is selected; 0, otherwise
Z_l	A binary variable, equal to 1 if backup supplier l is selected; 0, otherwise
E_m	Extra production capacity added to factory m
Q_{rnms}	Quantity of raw material type r transported from primary supplier n to factory m under scenario s
U_{rlms}	Quantity of the raw material type r transported from backup supplier l to factory m under scenario s
P_{ms}	Quantity of production in the factory m under scenario s
Y_{mjs}	Quantity of products transported from factory m to market zone j under scenario s
B_{js}	Quantity of lost sales in market zone j under the scenario s

Using the above notations, the stochastic bi-objective model can be formulated as follows:

$$Min\, Z_1 = \sum_{n\in N} x_n X_n + \sum_{l\in L} z_l Z_l + \sum_{m\in M} e_m E_m + \sum_{s\in S} \pi_s \left[\sum_{r\in R}\sum_{n\in N}\sum_{m\in M} \frac{q_{rnm} Q_{rnms}}{1-\delta_{rn}} + \sum_{r\in R}\sum_{l\in L}\sum_{m\in M} \frac{u_{rlm} U_{rlms}}{1-\gamma_{rl}} + \sum_{m\in M} p_m P_{ms} + \sum_{m\in M}\sum_{j\in J} y_{mj} Y_{mjs} + \sum_{j\in J} b_j B_{js} \right] \quad (6)$$

$$Max\, Z_2 = \sum_{s\in S} \pi_s \left[\sum_{r\in R}\sum_{n\in N}\sum_{m\in M} \frac{\alpha_n Q_{rnms}}{1-\delta_{rn}} + \sum_{r\in R}\sum_{l\in L}\sum_{m\in M} \frac{\beta_l U_{rlms}}{1-\gamma_{rl}} \right] \quad (7)$$

Subject to:

$$\sum_{r\in R}\sum_{m\in M} \frac{Q_{rnms}}{1-\delta_{rn}} \le (1-g_{ns})\, c_n X_n \qquad \forall n\in N, \forall s\in S \quad (8)$$

$$\sum_{r\in R}\sum_{m\in M} \frac{U_{rlms}}{1-\gamma_{rl}} \le f_l Z_l \qquad \forall l\in L, \forall s\in S \quad (9)$$

$$P_{ms} \le (1-v_{ms})(w_m + E_m) \qquad \forall m\in M, \forall s\in S \quad (10)$$

$$E_m \le k_m \qquad \forall m\in M \quad (11)$$

$$\sum_{n\in N} \frac{Q_{rnms}}{1-\delta_{rn}} + \sum_{l\in L} \frac{U_{rlms}}{1-\gamma_{rl}} = h_r P_{ms} \qquad \forall m\in M, \forall r\in R, \forall s\in S \quad (12)$$

$$P_{ms} = \sum_{j\in J} Y_{mjs} \qquad \forall m\in M, \forall s\in S \quad (13)$$

$$\sum_{j\in J} Y_{mjs} + B_{js} = d_j \qquad \forall j\in J, \forall s\in S \quad (14)$$

$$X_n \in \{0,1\} \qquad \forall n\in N \quad (15)$$

$$Z_l \in \{0,1\} \qquad \forall l\in L \quad (16)$$

$$E_m \ge 0 \qquad \forall m\in M \quad (17)$$

$$Q_{rnms} \ge 0 \qquad \forall n\in N, \forall r\in R, \forall m\in M, \forall s\in S \quad (18)$$

$$U_{rlms} \ge 0 \qquad \forall l\in L, \forall r\in R, \forall m\in M, \forall s\in S \quad (19)$$

$$P_{ms} \ge 0 \qquad \forall m\in M, \forall s\in S \quad (20)$$

$$Y_{mjs} \ge 0 \qquad \forall m\in M, \forall j\in J, \forall s\in S \quad (21)$$

$$B_{js} \ge 0 \qquad \forall j\in J, \forall s\in S \quad (22)$$

The objective function (6) minimizes the expected total costs of supply chain under different scenarios. The cost components are cost of evaluating and selecting primary and backup suppliers, cost of adding extra production capacity to factories, shipment cost from suppliers (both primary and backup suppliers) to factories, manufacturing cost, shipment cost from factories to market zones, and cost of lost sales, respectively. The objective function (7) maximizes the aggregate weighted sustainability scores of all suppliers under different scenarios. Constraints (8)-(10) enforce the capacity limitations of the primary suppliers, backup suppliers and factories, respectively. Constraint (11) imposes the maximum extendable production capacities in factories. Constraint (12) ensures the fulfillment of the required raw material in factories. Constraints (13) and (14) indicate the flow balance constraints in the factories and markets, respectively. Constraints (15)-(22) define the domain of the decision variables.

Now, we apply the augmented ε-constraint method to convert the bi-objective model into a single-objective formulation. The augmented ε-constraint method is amongst the most efficient and powerful multi-objective approaches (Fahimnia et al., 2015a; Mavrotas, 2009; Mavrotas and Florios, 2013; Torabi et al., 2015). Unlike many popular techniques (such as goal programming and weighted sum methods), the augmented ε-constraint approach obviates the need to assign weights to objectives. As an improved version of the original ε-constraint method, this approach avoids the production of weakly efficient (weakly Pareto) solutions and accelerates the solution by avoiding redundant iterations (Mavrotas, 2009). In the augmented ε-constraint method, one of the objective functions is optimized, whilst the other objectives are converted into constraints and an upper bound limit is set for each of them. Efficient solutions can be found by varying the bounds and solving the single-objective model. Let us assume a multi-objective model with k objective functions as follows:

$$Min_{X \in \chi} \{F(x) = (F_1(x), F_2(x), \ldots F_k(x))\}, \tag{23}$$

where X , χ and $F(x)$ indicate vector of decision variables, vector of k objective functions, and χ the space of feasible solutions, respectively. Based on the augmented ε-constraint method, the multi-objective problem in (23) can be transformed into the following single-objective in which only objective function $F_p(x)$ is optimized as the primary objective function and the other objective functions are treated as constraints.

$$Min_{X \in \chi} \{F_p(x) - \phi \times (\theta_1 + \theta_2 + \ldots + \theta_k)\} \tag{24}$$

Subject to

$$F_i(x) = \varepsilon_i - \theta_i \qquad \forall i \in \{1, 2, \ldots, K\} / \{k\} \tag{25}$$

Where variables $\theta_1, \theta_2, ..., \theta_k$ indicate surplus variables and parameters ε_i represent the bounds of respective constraints. Also, parameter ϕ takes a value in the interval of $[10^{-6}, 10^{-3}]$. For more details of the augmented ε-constraint technique, one can refer to (Mavrotas, 2009).

Applying the augmented ε-constraint method to our bi-objective optimization model, we convert the objective function (7) into a constraint with upper bound ε which is called *sustainability degree* hereafter. Therefore, the bi-objective model is converted to a single-objective model as follows:

$$Min\,(Z_1 - \phi \times \theta) \tag{26}$$

Subject to:

$$Z_2 = \varepsilon + \theta \tag{27}$$

Constraints (8)-(22).

4. Implementation and Discussion

4.1 Case problem

Plastic pipes have gradually supplanted competing materials (e.g., steel, copper and ductile iron) in many applications due to their low cost, installation ease, and performance advantages. World demand for plastic pipe is projected to rise by approximately 6.7 percent per annum through 2019 to 19.3 billion meters, where polyvinyl chloride (PVC) pipe accounts for the largest share of demand. PVC is utilized in various fields ranging from water supply and sewage to supply of electric power. In particular, efforts to expand access to potable water and sewage systems has boosted the demand for PVC pipe in water-scarce region of the Middle East (wpp, 2015). One of the leading manufacturers of PVC pipe in Middle East is Golpayegan Industrial Park (GIP). The PVC pipe manufactured by GIP is used widely in water supply and sewage structures. GIP has four factories[1] whose primary raw material are PVC powder, stabilizer and Calcium Carbonate. The required raw material at each factory can be supplied through a number of petrochemical companies (suppliers) located in Abadan, Isfahan, Golpayegan, Arak, Mahshahad, Boushehr and Kermanshah cities. The products are transported from factories to market zones including Tehran, Tabriz, Ahvaz, Razavi Khorasan, Yazd, Fars, Hamadan, Ilam and Ardebil

[1] Loolegostar Golpayegan factory: http://www.loolegostar.ir/fa
Tak Setare Golpayegan factory: http://taksetare.looleh.ir/fa
Polymer Golpayegan factory: http://pgproduct.com/fa/
Sahel Golpayegan factory: http://www.isomer.ir/profile/index/user/isomer-psag

provinces (here we only focus on the domestic market demand). Figure 3 shows the schematic view of the GIP's supply chain.

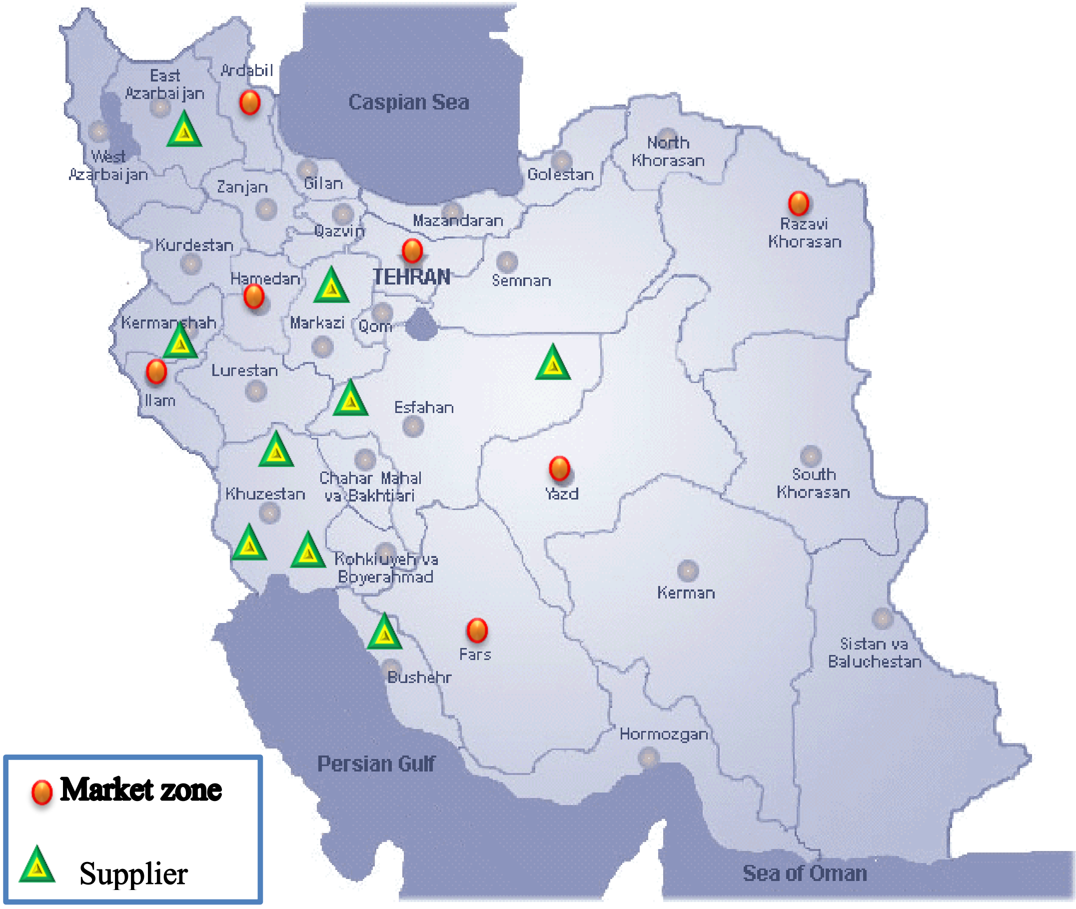


Figure 3. Geographical location of suppliers and market zones in GIP's supply chain

The sustainability performance of the suppliers has been evaluated based on the metrics outlined in IMPACT 2002+ (Jolliet et al., 2003) and GRI (GRI, 2011) as well as the sustainability criteria developed by National Petrochemical Company[2]. The main environmental measures involved safe treatment and disposal of hazardous materials (such as Hydrogen Peroxide), waste collection, emission of pollutants, and renewable and non-renewable energy consumption. The social criteria focused on human rights, labor working conditions, society contributions, and product responsibility issues. The economic measures included market shares, profitability and operating expenses.

Having the sustainability measures established, a panel of experts was formed to visit each supplier site for initial sustainability performance assessment against each of these criteria. The experts also

[2] National Petrochemical Company is a national entity that uses a number measures to assess the performance of petrochemical companies (http://english.nipc.ir/). In a same fashion, we use these environmental and social measures sustainability assessment of the suppliers.

evaluated the potential disruption risks at supplier sites and the factories to assist with developing disruption scenarios. Applying the fuzzy c-means clustering method, the disruption scenarios were grouped based on three scales of small, medium and large disruptions (each disruption cluster contains a number of related scenarios). To hedge against disruptions, three potential buttressing strategies were envisaged: (1) multiple sourcing strategy, (2) contracting with backup suppliers (the suppliers located in Tabriz and Ahvas were considered as backup suppliers), and (3) adding extra production capacity in factories.

The proposed hybrid approach was utilized to complete a resilience-sustainability analysis for GIP. The fuzzy c-means clustering method presented in Section 3.1 and the optimization model developed in Section 3.2, were coded in R2014b MATLAB and GAMS 24.1, respectively. All experiments were completed on a laptop with Intel Core i7-4702HQ CPU, 2.2 GHz with 16 GB of RAM. Following sections provide the numerical results and related sensitivity analyses. Please note that the runtimes are not reported as variations were shown to be negligible.

4.2 Analysis on the suppliers' performance

The output of the fuzzy c-means clustering method is depicted in Figure 4 providing the normalized scores of suppliers' performance in economic, environmental and social dimensions. As illustrated in Figure 4, the algorithm groups the suppliers into three clusters based on the scores obtained. Suppliers 1, 3, 5 and 8 are categorized as the most sustainable suppliers, whilst suppliers 6 and 7 are classified as suppliers with the lowest overall sustainability performance. The sustainability performance of the suppliers grouped into the second cluster (i.e., suppliers 2, 4 and 9) locates between those of suppliers in the first and third clusters.

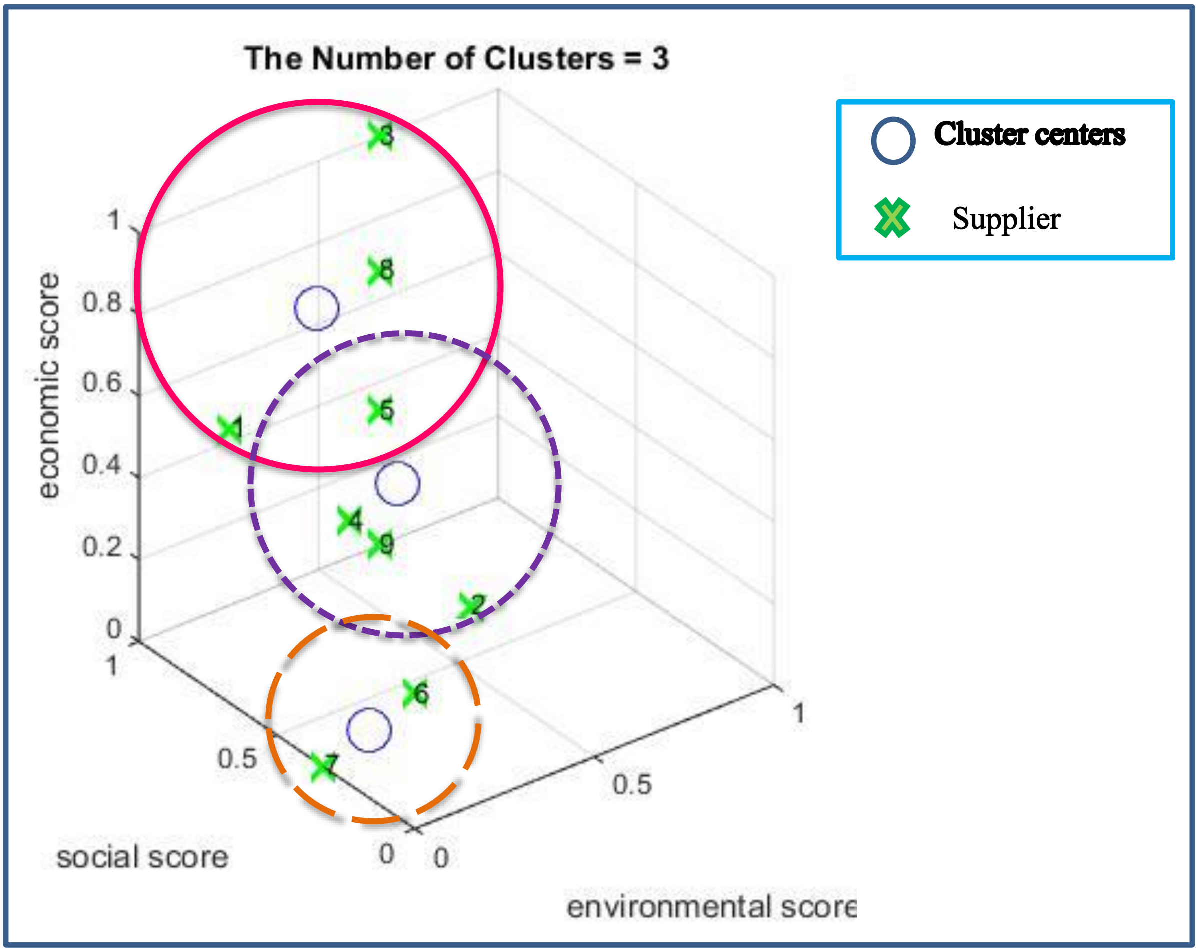


Figure 4. The output of fuzzy c-means clustering approach for the case problem

The sustainability performance of the third cluster does not meet the minimum requirement, suppliers 6 and 7 are excluded from the list of potential suppliers. To determine the quantities to purchase from the remainder of suppliers under each scenario of disruption, the bi-objective model developed in Section 3.2 was solved. For different sustainability degrees, Table 1 shows the percentage capacity of each supplier that is utilized to supply the required raw material at the factories given different disruption scales.

Table 1. The percentage capacity utilization of each supplier at different sustainability and disruption degrees

Sustainability Degree	Disruption Scale	Supplier					
		1	**2**	**3**	**4**	**5**	**8**
$\varepsilon = 8.1$	Small		97	100	100		1
	Medium		100	100	100		30
	Large		86	100	100	84	100
$\varepsilon = 8.2$	Small		79	100	100		34
	Medium		100	100	100		38
	Large		86	100	100	100	100
$\varepsilon = 8.3$	Small		69	100	100		44
	Medium		100	100	100	23	53
	Large		86	100	100	100	100
$\varepsilon = 8.4$	Small	79		100	100		62
	Medium	88		100	50	60	100
	Large	86		100	32	100	100
$\varepsilon = 8.5$	Small	94		95	55	33	79
	Medium	92		86	100	94	81
	Large	100		100	100	100	100
$\varepsilon = 8.6$	Small	100		100		100	83
	Medium	98		100	50	100	100
	Large	100		100	100	100	100
$\varepsilon = 8.7$	Small	100		100		100	77
	Medium	100		100		100	100
	Large	100		100	56	100	100

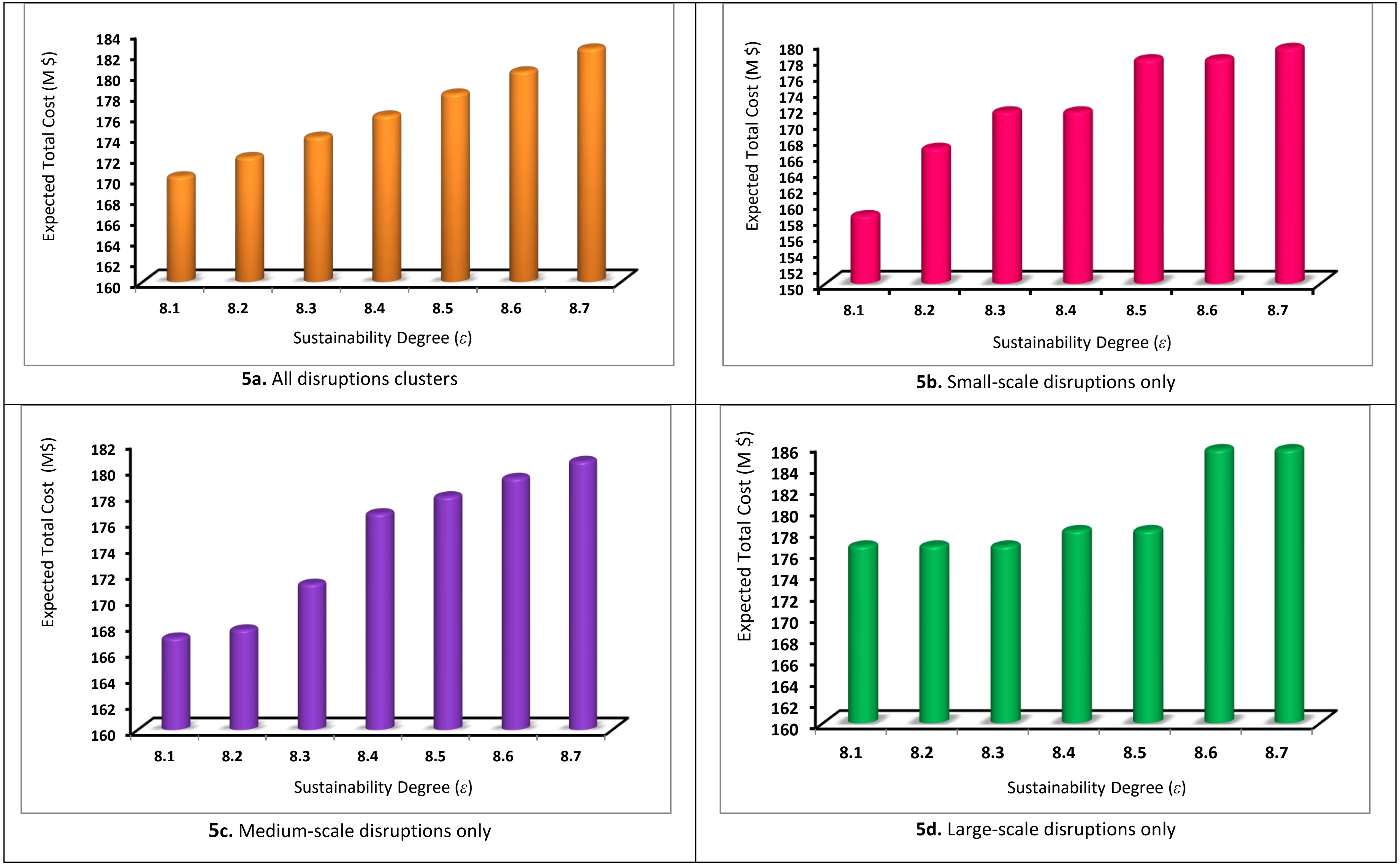
From Table 1, we observe that primary supplier 3 and backup supplier 8 serve factories in almost all situations. On the other hand, the backup supplier 9 is selected under no circumstances. In addition, suppliers 1, 2, 4, and 5 act as primary suppliers only in specific cases. These observations can be justified as follows. Suppliers 3 and 8 are recognized as the *most efficient suppliers* for GIP due to their desired performance in terms of sustainability and cost efficiency. While the sustainability performance of the backup supplier 8 is acceptable, its unattractive price prevents GIP from working with this supplier.

The selection of the suppliers 1, 2, 4 and 5 depends on the degrees of sustainability and disruption. Supplier 1 is a more expensive supplier with higher sustainability score compared to supplier 2. Thus, as the sustainability degree increases, suppliers 1 tends to be selected independent of disruption scale. More specifically, an optimal solution requires that supplier 2 is replaced with supplier 1 when the sustainability degree is higher than 8.4 (i.e., $\varepsilon \geq 8.4$). This may imply that the main roles of suppliers 1 and 2 are to contribute toward *enhancement of sustainability* and *cost efficiency*, respectively. A relatively analogous observation can be seen for suppliers 5 and 4. That is, supplier 5 is a more costly supplier with better sustainability performance when compared to supplier 4. Another observation is that with the rise in the scale of disruptions, the capacity utilization of suppliers 5 and 8 also increases.

This observation is independent of the sustainability degree. Therefore, we may conclude that suppliers 5 and 8 mainly contribute to building *resilience* against larger disruptions for GIP.

4.3 Analysis on the tradeoff between total cost and sustainability

In this section, we aim to explore the tradeoff between the total cost and overall sustainability performance of the GIP's supply chain. Such a tradeoff can be developed by varying the sustainability degree (ε) and solving the model (26) under constrains (8)-(22) and (27). The results are illustrated in Figure 5. The figure consists of four charts indicating the tradeoff between cost and sustainability for situations in which we account for a) all disruption clusters, b) small-scale disruptions only, c) medium-scale disruptions only, and d) large-scale disruptions only.



5a. All disruptions clusters

5b. Small-scale disruptions only

5c. Medium-scale disruptions only

5d. Large-scale disruptions only

Figure 5. Tradeoff between cost and sustainability for different disruption clusters

Not surprisingly, Figure 5a shows that the greater the sustainability degree is, the larger the total supply chain cost would be. When the degree of sustainability increases, supply chain tends to contract with more sustainable suppliers which may be more expensive and less robust to disruptions. What is more interesting though is the linear pattern of increase in the total cost with rise in sustainability degree of the supply chain. This finding can be helpful as it allows a decision maker to predict the expected total cost under disruption risks when planning for enhancing the sustainability performance of the supply chain.

Focusing on the scales of disruption can provide further insights regarding the relationship between sustainability and total cost. There are situations in Figures 5b and 5d upon which improving the sustainability degree does result in substantial growth in supply chain cost. For example, Figure 5.d indicates that as the sustainability degree is improved from 8.1 to 8.3, the supply chain cost is not influenced in case of large-scale disruptions. As opposed to Figure 5.c, moving from $\varepsilon = 8.3$ to $\varepsilon = 8.4$ in Figure 5.d leads to only a slight increase in total cost. A similar observation can be seen in Figures 5c for small-scale disruptions in the range of $8.3 \leq \varepsilon \leq 8.4$. This means that there may be opportunities enhance the supply chain sustainability, while remaining cost efficient under specific disruption scenarios.

4.4 Analysis on the effectiveness of buttressing strategies

As mentioned in section 3.1, GIP can potentially adopt the following strategies to hedge against disruptions: a) utilizing multiple sourcing strategy, b) contracting with backup suppliers, and c) adding extra production capacity to factories. We complete an experiment to evaluate the effectiveness of these strategies at different sustainability degrees. To this end, we calculate the total expected cost of GIP for cases in which the buttressing strategies include: 1) only multiple sourcing, 2) multiple sourcing as well as contracting with backup suppliers, 3) multiple sourcing and adding extra production capacity, and 4) all the aforementioned buttressing strategies. Figure 6 presents the results at four sustainability degrees.

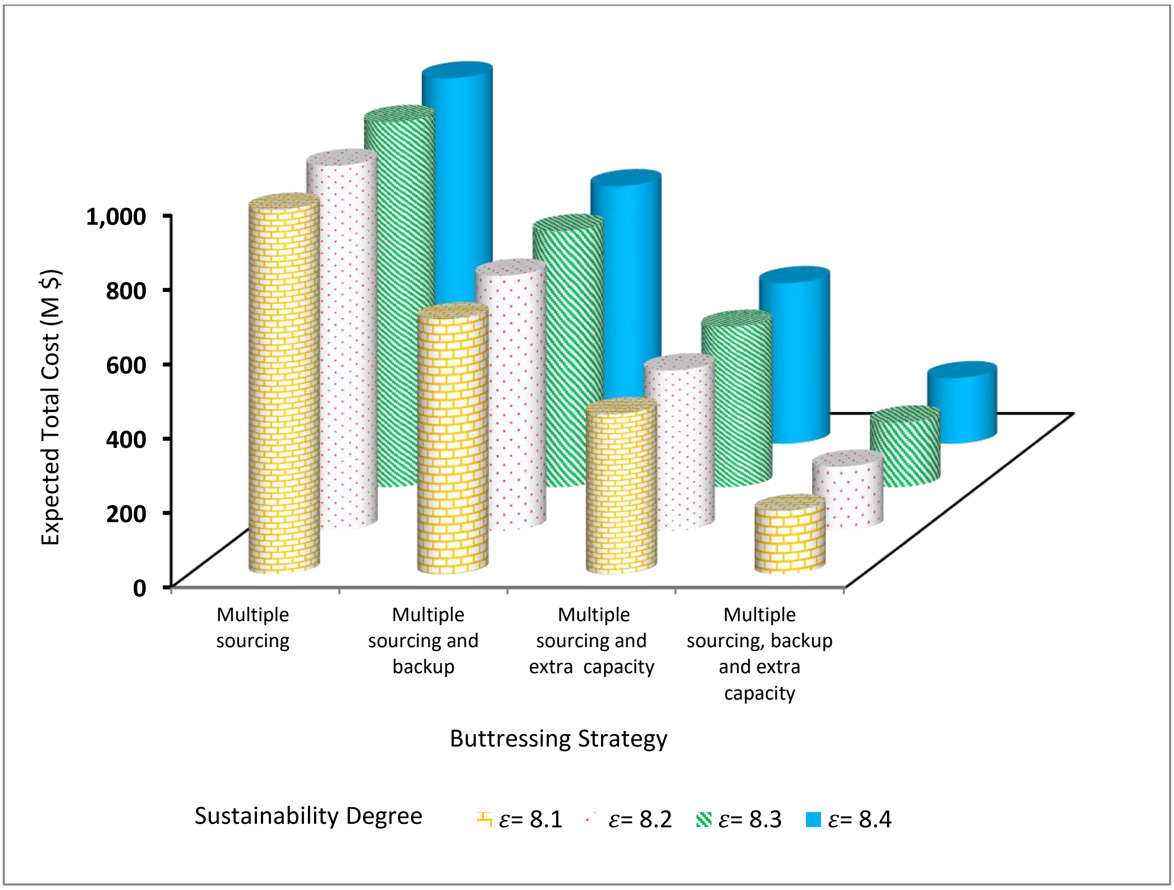


Figure 6. The cost performance of various buttressing strategies at different sustainability degrees

Figure 6 shows that all buttressing strategies are effective in reducing the expected total supply chain cost in disruptions. More precisely, comparing the expected total supply chain costs indicates that adopting the strategies of "backup supplier" and "extra capacity", in addition to "multiple sourcing strategy", can provide approximately 30% and 55% cost savings, respectively. The simultaneous adoption of the three buttressing strategies gains approximately 80% cost reduction benefits compared to the situation when only "multiple sourcing" strategy is used. These cost savings are almost analogous for different sustainability degrees meaning that the buttressing strategies can be consistently effective irrespective of the supply chain sustainability level.

4.5 Analysis on the impacts of suppliers' and factories' disruptions on total cost

Here, we examine how random disruptions at suppliers and factories can influence the expected total supply chain cost. At four sustainability levels, Figure 7 shows the percentage increase in expected total cost when either suppliers or factories or both supplier and factors are vulnerable to random disruptions. The figures consider the supply chain cost in the business-as-usual situation (i.e. when no facility and supplier is disrupted) as the baseline.

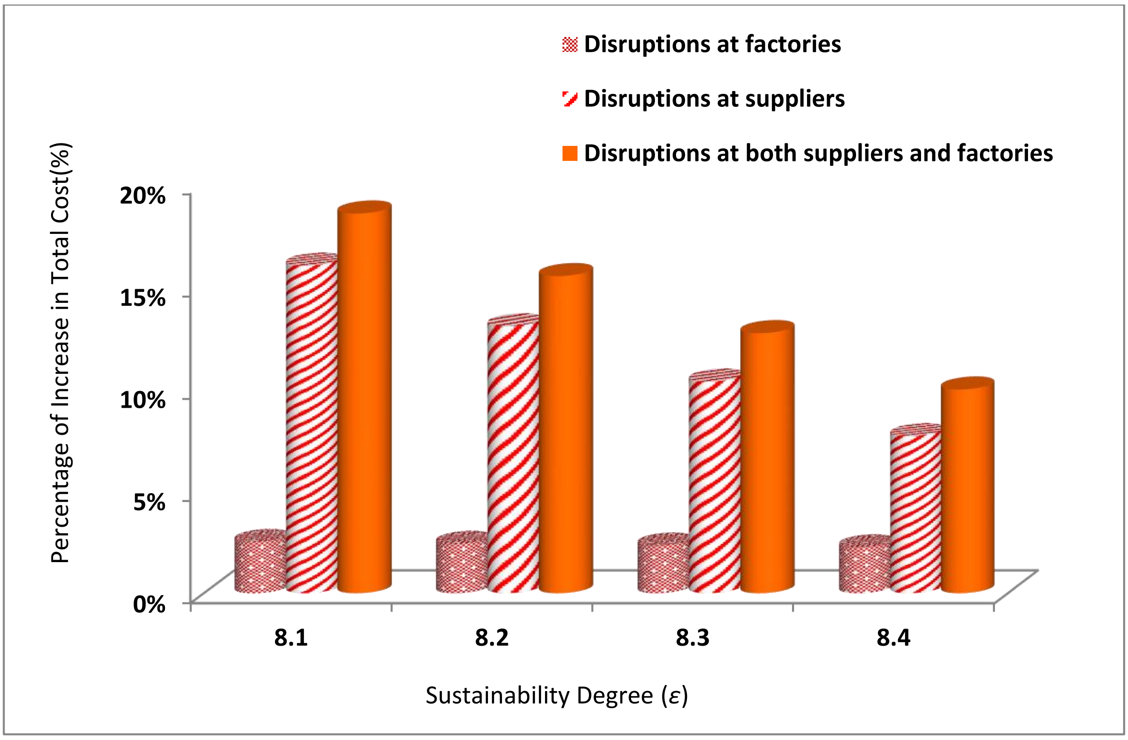


Figure 7. Percentage increase in total supply chain cost at different sustainability degrees for three disruption scenarios

Comparing the costs in Figure 7, we find that supplier disruptions can have greater impact on supply chain cost performance when compared to factory/production disruptions. This suggests that GIP needs to place more emphasis on and thus invest more on initiatives that prevent and/or mitigate supply-initiated disruptions. Another interesting observation is that the higher is the degree of sustainability, the lower is the percentage increase in total supply chain cost in disruption situations. In other words, as the supply chain becomes more sustainable, its cost performance is less affected in disruptions. This finding supports the idea that sustainability practices are supportive of enhanced supply chain resilience.

5. Conclusions

Sustainability initiatives and resilience strategies have been at the forethought of supply chain research and practice. Despite the broad and numerous supply chain modeling efforts addressing various sustainability and resilience topics, scanty literature exists on joint consideration of the two topics to explore the interrelationship and potential interactions. In this paper, we presented a hybrid methodology that can be used to design a resilient and sustainable supply chain. The proposed approach is implemented in two phases of "sustainability assessment" and "resilience enhancement". A fuzzy c-means clustering method was proposed to evaluate the overall sustainability performance of each supplier. A stochastic bi-objective optimization model was developed to determine outsourcing decisions and buttressing strategies that can help maintain the sustainability performance of the supply chain in random disruptions. The augmented ε-constraint technique was utilized to convert the bi-objective formulation into a single objective model.

We investigated the application of the proposed methodology in a real case study from plastic pipe industry. The hybrid approach was used to assess the contribution of each supplier to the supply chain resilience and sustainability. We showed, using our methodology, how tradeoff analysis can be used to identify the opportunities in which the supply chain can improve its sustainability performance whilst remaining cost efficient under various disruption scenarios. We also showed how the proposed approach can be used to examine the effectiveness of one buttressing strategy over another at different sustainability levels. From our case study, in particular, we found that sustainability practices are strongly supportive of supply chain resilience enhancement, evidenced by lower impact of disruptions on supply chain cost performance at higher sustainability degrees.

While we have shown the important insights that can be gained from implementing the proposed model and methodology, our study is not without limitations. These limitations can set the stage for future work in this important area of research. For instance, future research can investigate how sustainability-resilience tradeoffs can be influenced by operational risks caused by inherent interruptions such as uncertain customer demand, uncertain supply capacity, and uncertain procurement costs. Another direction for future research can be the incorporation of additional tactical and operational decisions such as facility location and routing decisions into the bi-objective model. Innovative solution methods are also needed for tackling larger-scale problems and dealing with extremely large datasets.

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