AN INTEGRATED PRINCIPAL COMPONENT ANALYSIS AND MULTI-OBJECTIVE MATHEMATICAL PROGRAMMING APPROACH TO AGILE SUPPLY CHAIN NETWORK DESIGN UNDER UNCERTAINTY

AZAM MORADI AND JAFAR RAZMI

School of Industrial Engineering
College of Engineering, University of Tehran
Tehran, Iran

REZA BABAZADEH*

Faculty of Engineering
Urmia University
Urmia, West Azerbaijan Province, Iran

ALI SABBAGHNA

School of Industrial Engineering
College of Engineering, University of Tehran
Tehran, Iran

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Abstract. The design of agile supply chain networks has attracted more attention in recent years according to the competitive business environment. Further, due to high degree of uncertainty in agile supply chains (SCs), developing robust and efficient decision making tools are of interest. In this study, an integrated approach based on principal component analysis (PCA) and multi-objective possibilistic mixed integer programming (MOPMIP) approaches is proposed to optimally design agile supply chain network under uncertainty. The PCA method is used for ranking and filtering the suppliers, constituting the first layer of the supply chain, based on agility criteria. The proposed MOPMIP model is employed to construct the agile supply chain network under uncertainty. In the proposed MOPMIP model, three objective functions including 1) total costs minimization, 2) total delivery time minimization and 3) maximization of flexibility are considered. An interactive fuzzy solution approach is used to solve the proposed MOPMILP model. Two numerical examples, is conducted to evaluate the performance and efficiency of the proposed integrated approach for agile supply chain network design under uncertainty.

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* Corresponding author: Tel.: +98 441 2972854; Fax: +98 441 2773591, Email address: r.babazadeh@urmia.ac.ir.

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1. **Introduction.** Nowadays, companies are facing a competitive business environment which brings challenges, such as how to design new products, manufacture them, increase share of market, raise flexibility, and bring innovation while simultaneously considering the improvement of production efficiency in response to customers and, thereby, reducing total costs. Companies, to survive in this competitive market, need an agile supply chain, minimizing lead time and maximizing responsiveness (Jacobs and Chase, 2017)[36]. The concept of agile manufacturing is proposed as a novel manufacturing paradigm in response to the above-mentioned challenges (Jitpaiboon, 2005)[39]. A supply chain network (SCN) includes; suppliers, manufacturers, distribution centers and customers that creates connections among the facilities as the edges of the network with the aim of acquiring raw materials and delivering final products to customers (Babazadeh and Razmi, 2012)[6].

Agile companies can properly work in a competitive uncertain environment where, market opportunities are continually emerging and changing. Furthermore, these companies can react immediately to such changes in the least possible time (Christopher et al., 2004; Suri, 2017)[14, 66]. To be truly agile, a SC must possess a number of distinguishing characteristics including market sensitivity, virtuality, process integration and network based structure (Christopher, 2000; Christopher et al., 2016)[15, 16].

Towill (2001)[67], investigated the main tiers of an agile SC and defined raw materials suppliers, manufacturers, distributors, retailers and customers as the main tiers of an agile SC. Christopher (2000)[15], studied the 21st century market demands and illustrated the world economic status and competitive forces as the main reasons of uncertainty. He proposed variety in goods and low quantities of order for the agile production. Agile supply chain network design (SCND) problem is a strategic level decision making problem (Chan et al., 2017)[13], in which the strategic and tactical level decisions such as the network structure and material flow are addressed. Therefore, optimally designed agile SCN will lead in total cost reduction, responsiveness increase and higher flexibility, thus will improve the total performance of the SC.

Principal component analysis (PCA) is a data reduction technique, using an orthogonal transformation to generate a set of values of linearly uncorrelated variables from linear composites of the set of observations of possibly correlated variables. The maximum number of new variables is equal to the number of original variables, and the new variables are uncorrelated with each other. PCA is widely used in supplier selection problem (Lam et al., 2010; Mak and Nebebe, 2016; Sarkis and Talluri, 2002)[42, 60, 43]. PCA gives weights with various outputs/input ratios based on multiple outputs and inputs of suppliers. Finally, a performance ranking of the suppliers according to PCA scores is conducted (Petroni and Braglia, 2000)[51]. Recently an informative and comprehensive review on PCA is presented by Jolliffe and Cadima (2016)[40]. Interested reader can refer to Padmashri and Sriraam (2017)[62], Olive (2017)[46] and At-Sahalia and Xiu (2017)[4] as new informative efforts on PCA application.

According to the above description, this study presents an integrated approach for optimal design of an agile SCN. First, based on agility measures, the suppliers are ranked via PCA method. Then, eligible suppliers are considered as candidate suppliers within the structure of an agile supply chain. In the second phase, a multi-objective possibilistic mixed-integer programming (MOPMIP) model is proposed to design a responsive, flexible, and agile SCN under uncertainty. The proposed model
is a multi-period, multi-commodity model which covers different transportation modes, flexibility, uncertainty and direct shipment of products.

The remainder of the paper is organized as follows. In the next section, the related literature is reviewed and investigated thoroughly to point out the research gap in SCND area and clarify the contributions of the proposed model. Section 3 includes the description and formulation of the proposed model. Section 4 is the defuzzification and calculation of equivalent auxiliary crisp model. The numerical results and illustrations are presented in Section 5. Finally, Section 6 concludes this paper and offers the possible future research directions.

2. Literature review. Agile SCND problem addresses the most important strategic level decisions (Stadtler, 2015)[64], affecting the ultimate performance and configuration of SCs. Studies in agility modeling area are categorized into two classes, namely conceptual models and mathematical programming models. In conceptual models, researchers have tried to define agility indices and measure the agility of organizations according to the defined criteria. Some studies focusing on conceptual models include Braunscheidel and Suresh (2009)[9], Carvalho et al. (2012)[11], Christopher et al. (2004)[14], Ganguly et al. (2009)[27], Hasan et al. (2012)[33], Razmi et al. (2011)[55] and Rola et al. (2016)[57].

Fayezi et al. (2017)[24], reviewed the body literature to point out the relationships and links between concepts of agility and flexibility within the SCs. In mathematical programming models, researchers have attempted to mathematically model agility measures in designing of a SCN. Since the focus of this study is on mathematical modeling of an agile SCN, the most relevant studies are reviewed. Gligor and Holcomb (2012)[30], explored the role of logistics capabilities in achieving SC agility through a multidisciplinary review of the relevant research. They provided the basis for formulating a conceptual framework of the relationship and conducted a review on the literature of manufacturing and SC agility from 1991 through 2010.

Supplier selection and supplier ranking problem has been investigated thoroughly throughout the SCM history in the literature, an early and comprehensive literature review on supplier selection was conducted by De Boer et al. (2001)[18]. Later many interesting and through efforts have been done in this area, interested readers may refer to (Chai et al., 2013; Razmi and Sabbaghnia, 2015; Kannan, 2018; Mukherjee, 2017)[12, 56, 41, 45]. A strong statistical tool to point out the important criteria in ranking the suppliers is PCA (Elsayed et al., 2017)[22]. This approach has been applied in many different areas (Fargani et al., 2017)[23] and here, it is applied to rank the possible suppliers of the considered SC.

Pan and Nagi (2013)[48], designed an agile SCN under assumptions of heavy demand and multi-customer environment. To reason heavy demands and capacity limits for production and transportation, they chose multiple companies in each echelon of SCN. Ambe (2010)[3], explored the concept of agile SCs and figured out the link between competitive advantages and agile SCs. He concluded, companies need to consider agility decisions to survive in a highly competitive business environment. Babazadeh et al. (2012)[5], designed single-product single-period agile supply chain. They considered main factors of agility such as market sensitivity, process integration, virtual integration and network orientation. Direct shipment, outsourcing, different transportation modes, discount, process integration, information among established facilities and maximum waiting time were the operational factors considered in their proposed model. Costantino et al. (2012)[17],
developed a SCN configuration strategy with a focus on the supply planning issue. They expressed the key supplier capacity constraints to take into account demands and maximum production capacities. Babazadeh and Razmi (2012) [6], designed an agile SC integrating production, outsourcing, discount, flexibility, and distribution activates, along with combining strategic and tactical decisions. Bachlaus et al. (2008) [7], designed a mathematical model of a five-echelon supply chain network to integrate production, distribution and logistics activities at the strategic decision-making level. Yusuf et al. (2004) [73], illustrated the technical need for the change of customers as the original reason for the development of agile supply chain and defined this need as the ability to compete with other companies. They considered concentration on flexibility and agility to respond customers with different needs at the correct time. Their theory was measured by conducting a study on 600 companies in England. They concluded that agility is an integral part of today’s supply chains. Wu and Barnes (2010) [69], considered the increasing importance of agile supply chains and, in particular, the significance of considering both quantitative and qualitative operational and strategic criteria.

Pishvaee and Torabi (2010) [53], considered a multi-objective possibilistic mixed integer programming (MOPMILP) model to dominate the problem of uncertainty in a closed-loop SCND problem. Their proposed approach has been widely used in addressing the uncertainties in SC literature (Fazli-Khalaf et al., 2017; Shaharudin et al., 2017; Sohi and Torabi, 2017) [25, 61, 63]. Wu and Barnes (2010) [69], considered the increasing importance of agile supply chains in general, and the significance of considering both quantitative and qualitative operational and strategic criteria in particular. Pan and Nagi (2010) [47], presented SC design problem under stochastic demands and utilized scenario-based stochastic programming approaches to tackle with demand uncertainties. Moreover, they integrated the design of SCN and production planning. You and Grossmann (2008) [72], presented a multi-period mixed integer nonlinear programming (MINLP) model for the bi-criterion optimization of economics and responsiveness objectives, under demand uncertainty and came up with a new approach for forecasting the safety stock levels. Hasani et al. (2012) [34], proposed a model for strategic SCND problem under interval data uncertainty and dealt with it via an interval robust optimization technique.

To the best of our knowledge and as the body of the literature shows, there is no research paper in the literature, developing a comprehensive approach based on PCA and multi-objective possibilistic programming approaches for an efficient agile SCND problem. Investigations on the literature shows that, the agile SCND models consider only some limited indices of agility in their modeling. In contrast, our approach, at first ranks the suppliers via real agility indices and then the eligible suppliers are considered to form the agile supply chain network.

3. The proposed integrated approach. The proposed integrated approach includes two phases. In the first phase, the orthogonal linear transformation PCA approach is employed to select the best agile suppliers among the primary suppliers. In the second phase, a multi-objective possibilistic programming model is developed to design an agile SCN, including suppliers, production centers, distribution centers and customers.

3.1. The principal component analysis (PCA) method. The PCA method generates new variables as the linear uncorrelated combination out of the original variables where the new axes or variables are called principal components, and the
value of new variables are principal component scores. The maximum number of new variable generation is equal to the number of original variables minus one. The new variables are uncorrelated with each other. The first linear combination of the variables accounts for the largest quantity of the variations in the sample; independently from the first combination, the second combination, accounts for the next largest quantity of the variations in the dimension, and so on. If a considerable value of total variance in the data is accounted for a few components, these few principal components can be used for explanation purposes followed by a data reduction techniques. PCA shows coordination of observations with respect to each of the axes assigned values to the new variables (Abdi and Williams, 2010; Bolch and Huang, 1973; Subhash, 1996)[65, 8, 1]. Moreover, PCA is a popular ranking method in multidimensional analysis (Rolland-Debord et al., 2017)[58]. An alternative to PCA is confirmatory factor analysis (CFA) (Brown, 2014; Harrington, 2009)[10, 32]. Although CFA can be applied on the same data and produces similar results based on a different mathematical model, PCA defines new measures for each input and output. The first requirement to define principal components is to compute eigenvalues. A rule-of-thumb for extracting the number of components is to consider the “eigenvalue greater than one” criterion. Finally, ranking the suppliers can be made according to PCA scores (Petroni and Braglia, 2000)[51]. To select the best agile suppliers, at first input/output attributes are defined, then each supplier is assessed according to the defined attributes via PCA approach. The most important supplier selection criteria’s (39 measures), extracted from literature investigations, are presented in Table 1. Next, the most effective supplier selection agility attributes (16 measures) are determined via conducting a brain storming meeting with experts. Further, supplier’s performances are assessed based on four output indicators presented in Table 3. Suppliers ranking via PCA approach is achieved by applying the indicators in Table 2 and Table 3. Then, the selected and specified agile suppliers are considered as the first layer of the agile SCN.

In the second phase, a multi-objective possibilistic programming model is developed to construct the optimum structure of an agile SCN. Also, the strategic and tactical level decisions such the numbers and location of facilities in different layers of the SCN, transportation modes and material flows between different nodes of the SCN are addressed. The objective functions include; cost minimization, responsiveness and flexibility maximization. Weighted-sum approach is conducted to cope with the objective functions of the proposed model. The proposed model has some non-linear equations and constraints, which needs to be linearized to reduce the complexity of the model. In the next subsection, the MOPMILP model is proposed.

Table 10 (in Appendix A), states the researches that have been investigated to point out the agility indicators proposed in Table 2 and Table 3.

3.2. Description of the proposed model. In this section, formulation of multi-period multi-product agile SCND is carried out under uncertainty. The goal of the model is to determine number, location and capacity of each facility in each period and amount of the product shipments between facilities. The optimal quantities of the production and inventory of different commodities are executed in different planning periods. The proposed model constructs an agile SCN through minimizing total costs, minimizing products delivery time, maximizing opened facilities flexibility and creating alliance (process and information integration) between different facilities in various layers and echelons of the chain. Figure 1 shows the structure
Table 1. The primary defined input attributes for suppliers selection

| Row | Input attribute                        | Row | Input attribute                        |
|-----|---------------------------------------|-----|---------------------------------------|
| 1   | Number of facilities                  | 21  | Working hours                         |
| 2   | Staff training                        | 22  | Bureaucratic                          |
| 3   | Education managers                    | 23  | Defective products                    |
| 4   | Standard simple mentation in organizations | 24  | Material requirements planning        |
| 5   | In Stock                               | 25  | Distribution plan                     |
| 6   | Product price                          | 26  | The geographical location of the factory |
| 7   | Product variety                        | 27  | The geographical area covered         |
| 8   | Transportation                         | 28  | The political situation in the regions covered |
| 9   | Waste                                  | 29  | Infrastructure                        |
| 10  | Market share                           | 30  | After Sales Service                   |
| 11  | Career Opportunities                   | 31  | Technical Support                     |
| 12  | The use of new technology              | 32  | Management                            |
| 13  | Production Volume                      | 33  | Response to Customer Request          |
| 14  | Automation                             | 34  | E-commerce Capability                 |
| 15  | Communication System                   | 35  | JIT                                   |
| 16  | Delivery                               | 36  | Packing Ability                       |
| 17  | Time of preparation                    | 37  | Position in the industry              |
| 18  | Lot Size                               | 38  | Product appearance                    |
| 19  | Work in process (WIP)                  | 39  | Quality                               |
| 20  | Specialist operators                   |     |                                       |

Table 2. The most important agility criteria filtered through conducting brain storming meeting

| Input indicators | Row                                |
|------------------|------------------------------------|
| 1                | Specialist operators               |
| 2                | The use of new technology          |
| 3                | Material requirements planning     |
| 4                | Distribution plan                  |
| 5                | Response to Customer Request       |
| 6                | Technical Support                  |
| 7                | E-commerce Capability              |
| 8                | Product variety                    |
| 9                | Production Volume                  |
| 10               | Transportation                      |
| 11               | After Sales Service                |
| 12               | Automation                         |
| 13               | Communication System               |
| 14               | JIT                                |
| 15               | Quality                            |
| 16               | The geographical area covered      |

Table 3. The performance indicators of suppliers

| Output indicators | Row                               |
|-------------------|-----------------------------------|
| 1                 | Product price                      |
| 2                 | Bureaucratic                       |
| 3                 | Delivery time                      |
| 4                 | Work in Process (WIP)              |
of the agile SCN including suppliers, plants, distribution centers, and customers. As illustrated, customers could be served by both distributors and plants based on cost, responsiveness and flexibility considerations. The main assumptions of the proposed model are as following:

- Customers demand, manufacturing costs, transportation costs, fixed costs, holding costs, alliance costs, delivery time, and minimum inventory level of the products in distribution centers have been tainted with uncertainty and are dealt with possibilistic programming.
- The potential locations of suppliers, plants, and distribution centers are known.
- The availability of different transportation modes are considered.
- The proposed model is a multi-period multi-product model.
- Inventory as safety stock is held in the distribution centers to deal with the demand uncertainties.
- The capacity of the facilities is not a constant parameter and is determined as a decision variable.
- Customer demand is satisfied either from distribution centers or by direct shipments from plants to customers.
- Alliance (Process and information integration) among opened facilities in different tiers should be considered.
- Shortage is not allowed.
- Lower and upper bound capacity of the opened facilities are enforced by modeling techniques during the planning horizon.

The following notations are used in formulation of the proposed model. To avoid any notation ambiguity, it should be noted that symbols with a tilde on indicate coefficients tainted with possibilistic uncertainty.

Indices
- $s$ Index of suppliers, $s = \{1 \ldots S\}$
- $p, f$ Index of plants, $p, f = \{1 \ldots P\}$
- $d, j$ Index of distribution centers, $d, j = \{1 \ldots D\}$
- $c$ Index of customers, $c = \{1 \ldots C\}$
- $t$ Index of time periods, $t = \{1 \ldots T\}$
- $l$ Index of transportation modes, $l = \{1 \ldots L\}$
- $i$ Index of products, $i = \{1 \ldots I\}$
- $m$ Index of materials, $m = \{1 \ldots M\}$

Parameters
- $f_{s}st$ Fixed cost of selecting supplier $s$ in period $t$
- $f_{p}pt$ Fixed cost of opening plant $p$ in period $t$
- $f_{d}dt$ Fixed cost of opening distribution center (DC) $d$ in period $t$
- $f_{s}sest$ Fixed cost of selecting supplier $s$ in period $t$
\[ f_{p,p} \] Fixed cost of utilizing plant \( p \) in period \( t \)
\[ f_{d,d,0} \] Fixed cost of utilizing DC \( d \) in period \( t \)
\[ d_{i,c,t} \] Demand of product \( i \) by customer \( c \) in period \( t \)
\[ v_{p,i,t} \] Manufacturing cost per unit of product \( i \) at plant \( p \) in period \( t \)
\[ H_{d,i,t} \] Holding cost per unit of product \( i \) at DC \( d \) in period \( t \)
\[ H_{p,i,t} \] Holding cost per unit of product \( i \) at plant \( p \) in period \( t \)
\[ Tr_{1,p,s,p,t} \] Transportation cost per unit (TCU) of product \( i \) from supplier \( s \) to plant \( p \) with Transportation mode (TM) \( l \) in period \( t \)
\[ Tr_{2,p,d,t} \] TCU of product \( i \) from plant \( p \) to DC \( d \) with TM \( l \) in period \( t \)
\[ Tr_{3,p,c,t} \] TCU of product \( i \) from plant \( p \) to customer \( c \) with TM \( l \) in period \( t \)
\[ Tr_{4,s,c,t} \] TCU of product \( i \) from DC \( d \) to customer \( c \) with TM \( l \) in period \( t \)
\[ \text{Cost}_{m,s,p,t} \] TCU of material \( m \) from supplier \( s \) to plant \( p \) in period \( t \)
\[ MI_{i,d,t} \] Minimum inventory of product \( i \) in DC \( d \)
\[ CPA_{1,p,f,t} \] Alliance cost between plants \( p \) and \( f \) in period \( t \)
\[ CPA_{2,d,j,t} \] Alliance cost between DC \( d \) and \( j \) in period \( t \)
\[ CPA_{p,d,t} \] Alliance cost between plant \( p \) and DC \( d \) in period \( t \)
\[ id_{p,cl,t} \] Delivery time (DT) from plant \( p \) to DC \( d \) with TM \( l \) in period \( t \)
\[ ic_{d,c,t} \] DT from DC \( d \) to customer \( c \) with TM \( l \) in period \( t \)
\[ ip_{d,t} \] DT from plant \( p \) to DC \( d \) with TM \( l \) in period \( t \)
\[ dis_{1,p,c,l,t} \] Distance between plant \( p \) and customer \( c \) with TM \( l \)
\[ dis_{2,d,c,l,t} \] Distance between DC \( d \) and customer \( c \) with TM \( l \)
\[ dis_{3,p,d,c,l,t} \] Distance between plant \( p \) and DC \( d \) with TM \( l \)

**Decision Variables**

\[ Xtr_{1,s,p,t} \] Quantity of material \( m \) shipped from supplier \( s \) to plant \( p \) with TM \( l \) in period \( t \)
\[ Xtr_{2,p,d,t} \] Quantity of products \( i \) shipped from plant \( p \) to DC \( d \) with TM \( l \) in period \( t \)
\[ Xtr_{3,p,c,t} \] Quantity of products \( i \) shipped from plant \( p \) to customer \( c \) with TM \( l \) in period \( t \)
\[ Xtr_{4,s,c,t} \] Quantity of products \( i \) shipped from DC \( d \) to customer \( c \) with TM \( l \) in period \( t \)
\[ X_{p,i,t} \] Quantity of products \( i \) manufactured in plant \( p \) in period \( t \)
\[ X_{s,m,i,p,t} \] Inventory of product \( i \) in plant \( p \) in period \( t \)
\[ X_{m,s,t} \] Inventory of material \( m \) in supplier \( s \) in period \( t \)
\[ X_{k,m,s,t} \] Quantity of material \( m \) bought from supplier \( s \) in period \( t \)
\[ X_{d,i,t} \] Inventory of product \( i \) in DC \( d \) in period \( t \)
\[ Cas_{s,t} \] Capacity of supplier \( s \) in period \( t \)
\[ Cap_{p,t} \] Capacity of plant \( p \) in period \( t \)
\[ Cap_{d,t} \] Capacity of DC \( d \) in period \( t \)
\[ CES_{s,t} \] Amount of capacity expansion of supplier \( s \) in period \( t \)
\[ CEP_{p,t} \] Amount of capacity expansion of plant \( p \) in period \( t \)
\[ CED_{d,t} \] Amount of capacity expansion of DC \( d \) in period \( t \)
\[ SF_{1} \] Flexibility of suppliers in period \( t \)
\[ PF_{1} \] Flexibility of plants in period \( t \)
\[ DCF_{1} \] Flexibility of DCs in period \( t \)
\[ DVF_{1} \] Flexibility of volume in period \( t \)
\[ As_{s,t} \] 1, if supplier \( s \) is active in period \( t \), otherwise 0
\[ Ap_{p,t} \] 1, if plant \( p \) is active in period \( t \), otherwise 0
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3.2.1. **Objective functions:** Three objective functions are developed to cope with the ultimate goals of decision-makers, namely, minimizing the SCND attributed costs, minimizing the material delivery time and maximizing the value of process and information integration.

\[ \text{Min } w_1 = \sum_{s,t} \tilde{f}_{st} \cdot As_{st} + \sum_{p,t} \tilde{f}_{pt} \cdot Ap_{pt} + \sum_{d,t} \tilde{f}_{dt} \cdot Ad_{dt} + \sum_{s,t} \tilde{f}_{se_{st}} \cdot Cas_{st} \]

\[ + \sum_{p,t} \tilde{f}_{pe_{pt}} \cdot Cap_{pt} + \sum_{d,t} \tilde{f}_{de_{dt}} \cdot Cad_{dt} + \sum_{i,p,t} X_{ip} \cdot \tilde{H}_{ip_{pt}} + \sum_{i,d,t} X_{id} \cdot \tilde{H}_{id_{dt}} \]

\[ + \sum_{i,p,t} X_{ip} \cdot \tilde{V}_{ip_{pt}} + \sum_{l,m,s,p,t} X_{1mspt} \cdot \tilde{Tr}_{1mspt} + \sum_{d,i,l,p,t} X_{2ipdlt} \cdot \tilde{Tr}_{2ipdlt} \]

\[ + \sum_{c,i,l,p,t} X_{3cilpt} \cdot \tilde{Tr}_{3cilpt} + \sum_{c,d,l,i,t} X_{4cdlit} \cdot \tilde{Tr}_{4cdlit} + \sum_{l,m,s,p,t} X_{1mspt} \cdot \tilde{Cost}_{mspt} \]

\[ + \sum_{f,p,t} \frac{1}{2} PA_{1fpt} \cdot \tilde{CPA}_{1fpt} + \frac{1}{2} PA_{2djt} \cdot \tilde{CPA}_{2djt} + \sum_{d,p,t} PA_{dpt} \cdot \tilde{CPA}_{dpt} \]

\[ \text{(1)} \]

\[ \text{Min } w_2 = \sum_{c,i,l,p,t} X_{2dipt} \cdot \tilde{id}_{dpt} \cdot \tilde{dis}_{3dlp} \]

\[ \text{Max } w_3 = DVF_t \]

Objective function (1) minimizes the total costs, including fixed selecting and utilizing costs, manufacturing costs, holding costs, transportation costs, material costs, and alliance costs. Objective function (2) minimizes the orders delivery time. Finally, objective function (3) maximizes flexibility of opened facilities within the network.

3.2.2. **Constraints:** Constraints of the proposed model can be subcategorized into main classifications, capacity related constraints e.g., equations (4) to (17) for different echelons of the chain, demand satisfaction restrictions e.g., equation (18), inventory handling and material flow balance constraints e.g., constraints (19)-(21) and (34), alliance creations considerations in different echelons of the chain e.g., equations (22)-(28) and (32) and (33), flexibility attributed restrictions e.g., constraints (29)-(32) and finally non-negativity and binary restrictions of the variables e.g., (35) and (36).

\[ \sum_{m,p,l} X_{1mspt} \leq Cas_{st} \quad \forall s,t \]

\[ Cas_{st} = Cas_{s(t-1)} + CES_{st} \quad \forall s,t \]

\[ Cas_{st} \leq \tilde{U_{bs}} \cdot As_{st} \quad \forall s,t \]

\[ Cas_{st} \geq \tilde{IBS} \cdot As_{st} \quad \forall s,t \]
\[
\sum_{i,d,l} X_{tr2_{ipdlt}} + \sum_{i,c,l} X_{tr3_{ipclt}} \leq Cap_{pt} \quad \forall p, t \\
\sum_{i} X_{ipt} \leq Cap_{pt} \quad \forall p, t \\
Cap_{pt} = Cap_{p(t-1)} + CEP_{pt} \quad \forall p, t \\
Cap_{pt} \leq \hat{UPB}.AP_{pt} \quad \forall p, t \\
Cap_{pt} \geq \hat{IPB}.AP_{pt} \quad \forall p, t \\
\sum_{i,c,l} X_{tr4_{idclt}} \leq cad_{dt} \quad \forall d, t \\
Cad_{dt} = Cad_{d(t-1)} + CED_{dt} \quad \forall d, t \\
Cad_{dt} \leq \hat{UBD}.Ad_{dt} \quad \forall d, t \\
Cad_{dt} \geq \hat{IBD}.Ad_{dt} \quad \forall d, t \\
\sum_{i} Xd_{idt} \leq cad_{dt} \quad \forall d, t \\
\sum_{l,p} X_{tr3_{ipct}} + \sum_{d,l} X_{tr4_{idclt}} \geq d\hat{e}_{ict} \quad \forall i, c, t \\
X_{s_{ms}} = X_{s_{ms(t-1)}} + X_{k_{ms}} - \sum_{p,l} X_{tr1_{msplt}} \quad \forall m, s, t \\
X_{ipt} = X_{ipt(-1)} + X_{ipt} - \sum_{d,l} X_{tr2_{ipdlt}} - \sum_{c,l} X_{tr3_{ipclt}} \quad \forall i, p, t \\
Xd_{idt} = Xd_{id(t-1)} + \sum_{d,l} X_{tr2_{ipdlt}} - \sum_{c,l} X_{tr3_{ipclt}} \quad \forall i, d, t \\
PA_{1pt} \leq AP_{pt} \quad \forall f, p \neq f, t \\
PA_{1pt} \geq \sum_{t} AP_{pt} + \sum_{t} AP_{ft} - 1 \quad \forall f, p \neq f, t \\
PA_{2dt} \leq \sum_{t} Ad_{dt} \quad \forall d, j \neq d, t \\
PA_{2dt} \geq \sum_{t} Ad_{dt} + \sum_{t} Ad_{dt} - 1 \quad \forall d, j \neq d, t \\
PA_{pdt} \leq \sum_{t} AP_{pt} \quad \forall d, p, t \\
PA_{pdt} \leq \sum_{t} Ad_{dt} \quad \forall d, p, t \\
PA_{pdt} \geq \sum_{t} Ap_{pt} + \sum_{t} Ad_{dt} - 1 \quad \forall p, d, t \\
SF_{t} = \sum_{i,s} \left( Cas_{st}.As_{st} - \hat{de}_{ict} \right) \quad \forall c, t \\
PF_{t} = \sum_{i,p} \left( Cap_{pt}.Ap_{pt} - \hat{de}_{cit} \right) \quad \forall c, t \\
DCF_{t} = \sum_{d,t} \left( Cad_{dt}.Ad_{dt} - \hat{de}_{cit} \right) \quad \forall c, t \\
DVF_{t} = min(SF_{t}, PF_{t}, DCF_{t}) \quad \forall c, t 
\]
\[
\sum_{i} X_{p_{ipt}} = \alpha \sum_{m,s,t} X_{tr1_{mspt}} \quad \forall p, t
\]

\[
X_{d_{dt}} \geq A_{dt}, M_{i_{dt}} \quad \forall i, d, t
\]

\[
X_{tr1_{mspt}}, \ldots, X_{2_{ipdt}}, X_{3_{ipdt}}, X_{4_{idlt}},
X_{p_{ipt}}, X_{ipt}, X_{s_{mst}}, X_{k_{mst}}, X_{d_{dt}},
\]

\[
C_{as_{st}}, C_{ap_{pt}}, C_{ad_{dt}}, C_{es_{st}}, C_{ep_{pt}}, C_{ed_{dt}},
S_{F}, P_{F}, D_{CE}, D_{VF_{m}} \geq 0 \quad \forall c, d, m, i, s, p, t
\]

Constraints (4) to (7) ensure the capacity related restrictions on the suppliers during the planning horizon. Constraint (4) is the warehousing capacity constraints on suppliers. Constraint (5) is indicating the developing capacity constraints on suppliers. Constraints (6) and (7) are upper and lower bound of limitations on supplier’s capacity. Constraints (8) through (12) are the same as constraint (4) to (7) for plants and are indicating the capacity related constraints on each plant. Constraint (9) illustrates that the quantity of products \(i\) being stored in plant \(p\) in period \(t\) should be less than the capacity of the same plant in that period. Constraints (13) through (16) are the same as constraints (4) to (7) for distribution centers. Constraint (17), same as constraint (9), indicates that the quantity of products \(i\) being stored in distribution center \(d\) in period \(t\) should be less than the capacity of the same distribution center in that period. Constraint (18) ensures that the customer’s demand is satisfied. Constraint (19) is an inventory control and material flow balance constraint for a supplier in each period. Constraint (20) is an inventory control and material flow balance constraint, controlling the logical relationship between input and output quantities for each plant at each period. Alike plants, constraint (21) is an inventory control and material flow balance constraint for a distribution center in each period. Constraint (22) expresses that an alliance among the plants of the agile SCN will be created via determining the active plants. Constraint (23) quarantines that each possible alliance will occur among opened facilities in production echelon of the SC. Constraints (24) and (25) are the same as constraints (22) and (23) to address the alliance creation between opened distribution centers. Constraints (26) and (27) express the required conditions for the creation of an alliance between the plants and distribution centers in different echelons. Constraint (28) ensures that for each plant and each distribution center during the planning horizon, an alliance will be created between them if a plant and a distribution center are established in different echelons. Constraints (29) to (31) calculate the flexibility of suppliers, plants and distribution centers. In this study, flexibility is defined as the difference between total capacity of facilities and the demand quantities. Actually, this value increases the flexibility of facilities in dealing with the changes of demands. The minimization of the obtained flexibility would be considered as the final flexibility volume. Constraint (32) and (33) are inventory control constraints, controlling the material shipments from suppliers to each plant at each period. Constraint (34) indicates that the amount of product \(i\) in each distribution center should be more than the minimum inventory level in each period. Finally, constraints (35) and (36) enforce the binary and non-negativity restrictions on corresponding to decision variables.

The proposed model is a multi-objective possibilistic mixed integer non-linear programming one. To solve the model the following steps are taken, converting
non-linear constraints into linear ones, developing equivalent crisp model and finally coping with objective functions to reach a single objective mathematical programming model. The detailed solution process is as following; at first, the proposed multi-objective non-linear model is reduced into a multi-objective possibilistic mixed integer linear programming (MOPMILP) model. Then, by applying an efficient possibilistic method proposed by Pishvaee and Torabi (2010)\[53\], an equivalent auxiliary crisp model is developed. After defuzzification, the weighted-sum approach is used to solve the crisp multi-objective model. Since the dimensions of cost, exibility and responsiveness are different, a normalized approach is followed to integrate the three objective functions into a single objective function. Therefore, the single objective function consisted of normalized costs, exibility and responsiveness, is represented as follows:

$$\text{Min } \text{obj} = \sum_{r=1, 2, 3} r.\text{norm}(w_r) = r_1.\text{norm}(w_1) + r_2.\text{norm}(w_2) - r_3.\text{norm}(w_3)$$ (37)

Where $$r_1 + r_2 + r_3 = 1$$ and coefficients $$r_1$$ to $$r_3$$ are weight coefficients of the objective functions, determined based on decision makers’ opinion and preferences.

3.3. Linearization of the proposed model. Non-linear problems in comparison with linear problems are usually harder to be solved. Hence, the proposed model is reformulated as a mixed-integer linear programming model, transformation into a linear programming requires several manipulations and substitutions. Constraint (29) is a non-linear equation, because of the multiplication of two decision variables. A new variable is defined as $$\text{SF}_{st}$$ which equals the multiplication of both $$\text{Cas}_{st}$$ and $$\text{As}_{st}$$ (i.e. $$\text{SFL}_{st} = \text{Cas}_{st}.\text{As}_{st}$$). Since $$\text{As}_{st} \in \{0, 1\}$$ and $$\text{Cas}_{st} \geq 0$$, the following constraints must be considered in the model:

$$0 \leq \text{SFL}_{st} \leq \text{Cas}_{st} \hspace{1cm} \forall s, t$$ (38)

$$\text{Cas}_{st} - N.(1 - \text{As}_{st}) \leq \text{SLF}_{st} \leq N.\text{As}_{st} \hspace{1cm} \forall s, t$$ (39)

Where, N is a large number. Then if $$\text{As}_{st} = 0$$, the right-hand side of inequality (39) equals zero and the left-hand side would be an enormous negative number. With respect to constraint (38), we have $$\text{SFL}_{st} = 0$$. On other hand, if $$\text{As}_{st} = 1$$, then inequalities (38) and (39) results in $$\text{Cas}_{st} = \text{SLF}_{st}$$. Considering, $$\text{SFL}_{st} = \text{Cas}_{st}$$, one can easily divide equation (39) into following constraints:

$$\text{Cas}_{st} - N.(1 - \text{As}_{st}) \leq \text{SLF}_{st} \hspace{1cm} \forall s, t$$ (40)

$$\text{SLF}_{st} \leq N.\text{As}_{st} \hspace{1cm} \forall s, t$$ (41)

Equations (30) and (31) are the same as equation (29) and could be linearized according to equations (42) to (49):

$$\text{PFL}_{pt} = \text{Cap}_{pt}.\text{Ap}_{pt} \hspace{1cm} \forall p, t$$ (42)

$$0 \leq \text{PFL}_{pt} \leq \text{Cap}_{pt} \hspace{1cm} \forall p, t$$ (43)

$$\text{Cap}_{pt} - N.(1 - \text{Ap}_{pt}) \leq \text{PLF}_{pt}$$ (44)

$$\text{PLF}_{pt} \leq N.\text{Ap}_{pt}$$ (45)

$$\text{DFL}_{dt} = \text{Cad}_{dt}.\text{Ad}_{dt}$$ (46)

$$0 \leq \text{DFL}_{dt} \leq \text{Cad}_{dt} \hspace{1cm} \forall d, t$$ (47)

$$\text{Cad}_{dt} - N.(1 - \text{Ad}_{dt}) \leq \text{DFL}_{dt} \hspace{1cm} \forall d, t$$ (48)

$$\text{DFL}_{dt} \leq N.\text{Ad}_{dt} \hspace{1cm} \forall d, t$$ (49)
For transforming the non-linear equation (32) to a linear equation, it could be replaced with the following constraints:

\[ DV F_t \leq SF_t \quad \forall c, t \quad (50) \]
\[ DV F_t \leq PF_t \quad \forall c, t \quad (51) \]
\[ DV F_t \leq DC F_t \quad \forall c, t \quad (52) \]

4. The equivalent auxiliary crisp model. An efficient possibilistic programming approach is applied to convert the proposed MOPMIP model into an equivalent auxiliary crisp model. Remarkably, the key part of the proposed possibilistic approach is based on Jiménez et al. (2007)[37], because of its several advantages as follow:

- The proposed approach is computationally effective because conserves linearity of the model and do not make the problem more complicated due not adding new objective functions and inequality constraints. Thus, the approach is widely used and implemented for large MILP models such as proposed SCND model.
- The ranking method(Jiménez, 1996)[38] can be applied on different membership functions, such as triangular, trapezoidal and even nonlinear membership functions in both symmetric and asymmetric forms.
- This approach is based on common mathematical concepts such as expected interval and expected value of fuzzy numbers.

Note that the Jiménez et al. (2007)[37] approach has newly been used as the defuzzification method in many related works in the SC planning area as well (e.g.,(Gholamian et al., 2015; Peidro et al., 2010; Pishvae and Razmi, 2012; Samani et al., 2017)[50, 52, 59, 29]).

The Jiménez et al. (2007)[37] approach is based on the concept of the expected value and expected interval of a fuzzy number. These concepts was firstly developed by Yager (1981)[70] and Dubois and Prade (1987)[20], and then followed by Heilpern (1992)[35] and Jiménez (1996)[38]. The membership function of a given triangular fuzzy number is as following:

\[
\mu_c(x) = \begin{cases} 
  f_c(x) = \frac{x-c^p}{c^m-c^p} & \text{if } c^p \leq x \leq c^m \\
  1 & \text{if } x = c^m \\
  g_c(x) = \frac{c^o-x}{c^o-c^m} & \text{if } c^m \leq x \leq c^o \\
  0 & \text{if } x \leq c^p \text{ or } x \geq c^o
\end{cases} \quad (53)
\]

The expected interval \((EI)\) and expected value \((EV)\) of triangular fuzzy number \(c\) based on Jiménez (1996)[38], can be defined as follow:

\[
EI(\tilde{c}) = [E^{c}_{1}, E^{c}_{2}] = [\int f_c^{-1}(x)dx, \int g_c^{-1}(x)dx] = \left[ \frac{1}{2}(c^p + c^m), \frac{1}{2}(c^m + c^o) \right] \quad (54)
\]
\[
EV(\tilde{c}) = E^{c}_{1} + E^{c}_{2} = \frac{c^p + 2c^m + c^o}{4} \quad (55)
\]

According to the Jiménez (1996)[38] ranking approach, for any pair of fuzzy numbers \(\tilde{a}\) and \(\tilde{b}\), the degree, in which \(\tilde{a}\) is greater than \(\tilde{b}\) is defined as follows:

\[
\mu_M(\tilde{a}, \tilde{b}) = \begin{cases} 
  0 & \text{if } E^{a}_{2} - E^{b}_{1} < 0 \\
  \frac{E^{a}_{2} - E^{b}_{1}}{E^{a}_{2} - E^{b}_{1} - (E^{a}_{1} - E^{b}_{2})} & \text{if } 0 \in [E^{a}_{1} - E^{b}_{2}, E^{a}_{2} - E^{b}_{1}] \\
  1 & \text{if } E^{a}_{1} - E^{b}_{2} > 0
\end{cases} \quad (56)
\]
When \( M(\tilde{a}, \tilde{b}) \geq \alpha \) it will be said that \( \tilde{b} \) is smaller than, or equal to \( \tilde{a} \) at least in degree of and it will be represented as \( \tilde{a} \geq \alpha \tilde{b} \). It should be noted that the ranking method of Jiménez (1996)\[38\] is somehow like the proposed approaches by Gonzlez (1990)\[31\] and Fortemps and Roubens (1996)\[26\]. Also, for more details on fuzzy number ranking, the interested readers may refer to Dubois et al. (2000)\[21\]. Based on Parra et al. (2005)\[49\], for any pair of fuzzy numbers \( \tilde{a} \) and \( \tilde{b} \), it will be said that \( \tilde{a} \) is indifferent (equal) to \( \tilde{b} \) in degree, if the following relationships hold simultaneously:

\[
\tilde{a} \geq_{\alpha/2} \tilde{b}, \quad \tilde{a} \leq_{\alpha/2} \tilde{b}
\]  

(57)

The above equations can be revised as follows:

\[
\alpha/2 \leq \mu_M(\tilde{a}, \tilde{b}) \leq 1 - \alpha/2
\]  

(58)

Now, given that all the parameters are considered to be triangular or trapezoidal fuzzy numbers, to work more convenient we develop the compact form of the proposed model as follows:

\[
\min z = \tilde{c}^t x
\]

s.t.

\[
\tilde{a}_i x^3 \geq b_i, \quad i = 1, \ldots, l
\]

\[
\tilde{a}_i x = b_i, \quad i = l + 1, \ldots, m
\]

\[
x \geq 0
\]

These equations can be revised as follows:

\[
\left\{
\begin{array}{l}
E^a_{2i} x - E^b_{1i} \geq \alpha, \quad i = 1, \ldots, l \\
\alpha/2 \leq E^a_{2i} x - E^b_{1i} \leq 1 - \alpha/2, \quad i = l + 1, \ldots, m
\end{array}
\right.
\]  

(60)

Also, by using ranking method of Jiménez (1996)\[38\], it can be showed (see Jiménez et al., 2007)\[37\] that a feasible solution like \( x_0 \) is an -suitable optimal solution of model (23) if and only if for all feasible decision vectors say \( x \) such that \( \tilde{a}_i x \geq_{\alpha} \tilde{b}_1, i = 1, \ldots, l \), and \( \tilde{a}_i x \approx_{\alpha} \tilde{b}_1, i = l + 1, \ldots, m \), the following equation holds:

\[
\tilde{c}^t x \geq \frac{1}{2} \tilde{c}^t x^0
\]  

(62)

Thus, \( x_0 \) is a better choice (with the objective of minimizing) at least in degree 1/2 as faced to the other feasible vectors. The above equation can be revised as follows:

\[
\frac{E^a_{2i} x + E^b_{1i} x}{2} \geq \frac{E^a_{2i} x^0 + E^b_{1i} x^0}{2}
\]  

(63)
Therefore, using the definition of expected interval and expected value of a fuzzy number, the equivalent crisp-parametric model of the reduced model (59) can be written as follows:

\[
\min \ E \left( \hat{c} \right) x \\
\text{s.t.} \\
\left[ (1 - \alpha)E_{a_i}^2 + \alpha E_{a_i}^1 \right] x \geq \alpha E_{b_i}^2 + (1 - \alpha)E_{b_i}^1, \quad i = 1, \ldots, l \\
\left[ (1 - \frac{\alpha}{2})E_{2}^2 + \frac{\alpha}{2} E_{1}^1 \right] x \geq \frac{\alpha}{2} E_{2}^2 + (1 - \frac{\alpha}{2})E_{1}^1, \quad i = l + 1, \ldots, m \\
\left( \frac{\alpha}{2} E_{2}^2 + (1 - \frac{\alpha}{2})E_{a_i}^1 \right] x \leq \left( 1 - \frac{\alpha}{2} \right) E_{b_i}^2 + \frac{\alpha}{2} E_{1}^1, \quad i = l + 1, \ldots, m \\
x \geq 0
\] (64)

According to model (64), the equivalent auxiliary crisp model of the agile SCND model can be developed easily. As it is clear from model (64), each constraint from the proposed model containing a parameter tainted with uncertainty will be divided into three main constrains; respectively \(i = 1, \ldots, l\) and two set of constraints for \(i = l + 1, \ldots, m\). In objective function(s), the expected value of the uncertain parameters will be replaced with them respectively. These modifications change the proposed multi-objective possibilistic mixed integer linear programming (MOPMILP) model into a crisp multi-objective mixed integer linear programing model. To cope with the objective functions, as discussed earlier, the weighted-sum approach is applied on the model.

5. Computational results. In the test problem, conducted to be solved by the proposed agile SCND approach, the cardinality of the primary suppliers set is 60. To select the most agile suppliers based on the pre-defined attributes, the PCA method is applied. Table 11, in Appendix A shows the agile suppliers’ attributes for the suppliers set. These measures are driven out from the normalized values of the four performance factors and the 60 input attributes. The decision-maker would like to select the suppliers with the best possible combination of the performance parameters. Principal component analysis is a ranking procedure, identifying deserted and outlying suppliers regardless of the performance parameter of the vendor. Most of the data set variations is caused from the first few linear combinations of variables, i.e., the principal components. In other words, PCA is employed to identify the principal components with different linear combinations so that they can be multiplied by their eigenvalues to obtain a weighted measure of the variables. The first step in PCA is testing the correlation level of the variables. To this extent, both the correlation matrix and the coefficients are the usual Pearson correlations (one-tailed) and confirm that significant correlations can be found. A rule-of-thumb for determining the number of extracted components is to consider the “eigenvalues greater than one” criterion. The so-called “eigenvalue scree plot” is often useful in graphically determining the number of extracted factors as shown in Figure 2.

In the present analysis, seven components are workable solutions and the residual components have eigenvalues greater than 1 (see Figure 2). Table 4 shows the variance of 16 components. The first seven components account for approximately 64 percent of the total variance of the variables as shown in Table 5. The percentage of the variances explained by each component represents its relative importance.

Usually, the interpretable results cannot be extracted from initial components. One of the purposes of rotation is to obtain the most interpretable components. In other words, rotation brings about the larger loading of the different variables on
Figure 2. Eigenvalue scree plot

Table 4. Total Variance of components

| Component | Initial Eigenvalue | Total | Percentage of Variance | Cumulative Percentage |
|-----------|--------------------|-------|-------------------------|-----------------------|
| 1         | 2.074              | 12.965| 12.965                  |                       |
| 2         | 1.803              | 11.267| 24.232                  |                       |
| 3         | 1.575              | 9.843 | 34.075                  |                       |
| 4         | 1.380              | 8.625 | 42.700                  |                       |
| 5         | 1.334              | 8.336 | 51.036                  |                       |
| 6         | 1.181              | 7.383 | 58.419                  |                       |
| 7         | 1.027              | 6.418 | 64.836                  |                       |
| 8         | 0.935              | 5.841 | 70.677                  |                       |
| 9         | 0.884              | 5.523 | 76.200                  |                       |
| 10        | 0.793              | 4.959 | 81.159                  |                       |
| 11        | 0.720              | 4.498 | 85.656                  |                       |
| 12        | 0.624              | 3.898 | 89.554                  |                       |
| 13        | 0.580              | 3.624 | 93.178                  |                       |
| 14        | 0.423              | 2.642 | 95.820                  |                       |
| 15        | 0.362              | 2.265 | 98.086                  |                       |
| 16        | 0.306              | 1.914 | 100.000                 |                       |

Table 5. Total Variance of components

| Component | Extraction Sums of Squared Loadings | Rotation Sums of Squared Loadings |
|-----------|-------------------------------------|----------------------------------|
|           | Total | Percentage of Variance | Cumulative Percentage | Total | Percentage of Variance | Cumulative Percentage |
| 1         | 2.074 | 12.965 | 12.965 | 1.548 | 9.675 | 9.675 |
| 2         | 1.803 | 11.267 | 24.232 | 1.547 | 9.672 | 19.347 |
| 3         | 1.575 | 9.843  | 34.075 | 1.510 | 9.440 | 28.787 |
| 4         | 1.380 | 8.625  | 42.700 | 1.506 | 9.430 | 38.197 |
| 5         | 1.334 | 8.336  | 51.036 | 1.460 | 9.126 | 47.324 |
| 6         | 1.181 | 7.383  | 58.419 | 1.401 | 8.757 | 56.081 |
| 7         | 1.027 | 6.418  | 64.836 | 1.401 | 8.755 | 64.836 |
each component both greater and smaller than previous. There are a number of
different methods of extraction; here, the varimax rotation approach (Portes and
Aguirre, 2016)[54] has been conducted. The “rotated” loadings of each variable on
each component are reported in Table 6. The interpretation of Table 6 helps the
decision-maker to conclude that each component loads on matters concerning the
variables.

For each variable, a coefficient \( w_i \), \( i = 1,\ldots,16 \) is obtained by multiplying the
loading of each component by the variance percentage of that component. For
instance, \( w_1 \) is calculated as follows:

\[
 w_1 = 0 \times 0.12965 + 0 \times 0.11267 + 0.615 \times 0.9843 \\
+ 0 \times 0.8625 + 0 \times 0.8336 + 0 \times 0.7383 + 0 \times 0.6418 \\
= 0.69
\]  

(65)

The coefficients \( w_2 \) to \( w_{16} \) are calculated with the same manner. Each coefficient
is then multiplied by the corresponding variable’s value (in1 to in16) for each
supplier in order to obtain a final score for supplier as shown in Table 7. The final
ranking is obtained based on Table 7’s scores. As it is clear from the score values,
supplier #13 ends up as the selected supplier, providing the best performance with
respect to the seven identified components. Finally, 7 suppliers are the superior
group among the 60 suppliers and therefore these suppliers are considered as the
agile SCN’s suppliers. The IBM® SPSS® Statistics v22 software on a personal
computer with 4 GB RAM and Inter® Core™ i7-5500U CPU is used to apply PCA
technique.

The performance of the proposed model is evaluated and assessed through two
test problem. Test problems are solved with GAMS 24.1.2 software on a personal
computer with 4 GB RAM and Intel® Core™ i7-5500U CPU. The required in-
put parameters are generated according to the information provided in Table 8
motivated and extracted from Babazadeh et al. (2012)[5].

| Variables | Components |
|-----------|------------|
|           | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
| X1        | 0.042 | -0.192 | 0.615 | -0.211 | 0.159 | -0.273 | -0.029 |
| X2        | -0.175 | 0.176 | -0.015 | -0.065 | -0.709 | -0.101 | -0.061 |
| X3        | -0.083 | -0.096 | -0.145 | 0.479 | -0.440 | 0.219 | -0.067 |
| X4        | 0.120 | 0.177 | -0.220 | 0.609 | 0.221 | -0.251 | -0.108 |
| X5        | -0.208 | -0.827 | 0.065 | 0.139 | 0.048 | 0.263 | 0.109 |
| X6        | -0.223 | 0.571 | -0.207 | 0.099 | 0.256 | 0.182 | 0.418 |
| X7        | 0.133 | -0.134 | 0.205 | 0.753 | -0.070 | 0.073 | 0.037 |
| X8        | -0.073 | 0.004 | -0.090 | -0.018 | -0.016 | -0.729 | -0.123 |
| X9        | 0.841 | 0.035 | 0.135 | 0.022 | 0.083 | -0.011 | 0.014 |
| X10       | -0.110 | 0.228 | 0.695 | 0.221 | 0.190 | 0.141 | -0.097 |
| X11       | -0.258 | 0.541 | 0.155 | 0.034 | -0.283 | 0.292 | 0.244 |
| X12       | 0.175 | -0.166 | -0.147 | -0.281 | 0.151 | 0.506 | -0.591 |
| X13       | -0.177 | 0.115 | -0.637 | 0.014 | 0.262 | -0.176 | 0.244 |
| X14       | -0.464 | 0.159 | 0.031 | -0.086 | 0.629 | -0.029 | 0.048 |
| X15       | 0.111 | 0.005 | -0.030 | -0.163 | 0.072 | 0.191 | 0.861 |
| X16       | -0.073 | 0.004 | -0.090 | -0.018 | -0.016 | -0.729 | -0.123 |
Table 7. Suppliers scores driven out via PCA approach

| Supplier | Score | Supplier | Score | Supplier | Score | Supplier | Score |
|----------|-------|----------|-------|----------|-------|----------|-------|
| 1        | -0.44143 | 16       | -0.45093 | 31       | -0.70673 | 46       | 0.22046 |
| 2        | -0.39948 | 17       | -0.16193 | 32       | 0.52357  | 47       | 0.646209 |
| 3        | 0.079517 | 18       | 0.41908  | 33       | 0.574339 | 48       | -0.2407 |
| 4        | -0.01854 | 19       | 0.05046  | 34       | 0.054961 | 49       | 0.430716 |
| 5        | 0.06819  | 20       | 0.010264 | 35       | -0.3108  | 50       | 0.175306 |
| 6        | -0.16339 | 21       | -0.29805 | 36       | -0.29681 | 51       | -0.12202 |
| 7        | -0.47472 | 22       | 0.283236 | 37       | 0.379933 | 52       | 0.065461 |
| 8        | -0.26409 | 23       | -0.10214 | 38       | 0.083386 | 53       | -0.80726 |
| 9        | 0.359434 | 24       | -0.3874  | 39       | -0.11785 | 54       | -0.19505 |
| 10       | -0.48728 | 25       | 0.278027 | 40       | 0.092893 | 55       | 0.258526 |
| 11       | 0.044161 | 26       | 0.196247 | 41       | -0.19233 | 56       | 0.098087 |
| 12       | 0.50004  | 27       | 0.194767 | 42       | 0.121639 | 57       | 0.265066 |
| 13       | 1.064131 | 28       | 0.009783 | 43       | -0.39538 | 58       | 0.098087 |
| 14       | -0.72305 | 29       | -0.08439 | 44       | 0.676464 | 59       | -0.50213 |
| 15       | -0.19635 | 30       | 0.266653 | 45       | 0.08386  | 60       | -0.39293 |

Table 8. The sources of random generation of the most likely values

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $\tilde{f}_{st}$ | $\sim$ Uniform(1800000, 4300000) | $\tilde{f}_{pt}$ | $\sim$ Uniform(1700000, 4000000) |
| $\tilde{f}_{dt}$ | $\sim$ Uniform(1600000, 3000000) | $\tilde{f}_{se_{st}}$ | $\sim$ Uniform(180000, 480000) |
| $\tilde{f}_{pe_{st}}$ | $\sim$ Uniform(170000, 400000) | $\tilde{f}_{de_{st}}$ | $\sim$ Uniform(160000, 3000000) |
| $\hat{d}_{ict}$ | $\sim$ Uniform(100, 200) | $\hat{v}_{ipt}$ | $\sim$ Uniform(120, 150) |
| $\hat{H}_{dt}$ | $\sim$ Uniform(10, 30) | $\hat{H}_{ipt}$ | $\sim$ Uniform(15, 40) |
| $\hat{T}_{r1_{ipt}}$ | $\sim$ Uniform(80, 100) | $\hat{T}_{r2_{ipt}}$ | $\sim$ Uniform(40, 60) |
| $\hat{T}_{r3_{ipt}}$ | $\sim$ Uniform(110, 200) | $\hat{C}_{PA_{1p_{ft}}}$ | $\sim$ Uniform(50000, 60000) |
| $\hat{C}_{PA_{2d_{lt}}}$ | $\sim$ Uniform(30000, 35000) | $\hat{C}_{PA_{pdt}}$ | $\sim$ Uniform(60000, 70000) |
| $\hat{M}_{id_{t}}$ | $\sim$ Uniform(10, 30) | $\hat{I}_{d_{clt}}$ | $\sim$ Uniform(2, 4) |
| $\hat{I}_{d_{clt}}$ | $\sim$ Uniform(2, 4) | $\hat{I}_{e_{dlt}}$ | $\sim$ Uniform(10, 16) |
| $\hat{I}_{e_{dlt}}$ | $\sim$ Uniform(10, 16) | $\hat{d}_{1_{pct}}$ | $\sim$ Uniform(200, 600) |
| $\hat{d}_{2_{dlt}}$ | $\sim$ Uniform(300, 500) | $\hat{d}_{3_{pct}}$ | $\sim$ Uniform(100, 200) |

The indices of the first test problem are: 3 periods, 15 customers, 7 suppliers, 3 plants, 8 distribution centers, 2 transportation modes, 2 products and 5 materials and for the second test problem they are: 6 periods, 30 customers, 14 suppliers, 6 plants, 16 distribution centers, 5 transportation modes, 5 products and 10 materials. In Table 9 the optimal solutions for different values of importance coefficients (i.e., $r$) for both test problems are presented. Here, as it’s clear from the reported values, as the value of the importance coefficient raises (for the first two objectives) the value of the objective function drops to its best possible value. This trend is traceable on both test problem and on all the objective function values on Table 9. To investigate the objective functions values presented on Table 9, Figure 3 depicts the normalized Pareto solutions of first test problem’s objective function values. As we learn from the figure, the objective functions are opposing each other. The decision maker’s preferences are the final measure to choose a specific importance coefficient values.
Table 9. The Pareto optimal solution for different values of importance coefficients

| r1 | r2 | r3 | Problem No. | Obj1       | Obj2       | Obj3       | CPU time (Sec) |
|----|----|----|-------------|------------|------------|------------|----------------|
| 1  | 0  | 0  | 1           | 3.69E+11   | 1.38E+08   | 0.00E+00   | 134            |
|    |    |    | 2           | 3.82E+12   | 1.26E+09   | 0.00E+00   | 646            |
| 0  | 1  | 0  | 1           | 6.61E+12   | 2.44E+07   | 0.00E+00   | 164            |
|    |    |    | 2           | 2.50E+15   | 2.53E+08   | 0.00E+00   | 655            |
| 0  | 0  | 1  | 1           | 6.61E+12   | 1.38E+08   | 7.46E+07   | 132            |
|    |    |    | 2           | 2.50E+15   | 1.26E+09   | 3.74E+11   | 692            |
| 0.45| 0.45| 0.1 | 1           | 3.39E+12   | 7.89E+07   | 1.42E+07   | 210            |
|    |    |    | 2           | 1.13E+15   | 6.58E+08   | 8.33E+10   | 512            |
| 0.35| 0.35| 0.3 | 1           | 3.99E+12   | 9.30E+07   | 2.76E+07   | 167            |
|    |    |    | 2           | 1.30E+15   | 7.29E+08   | 1.46E+11   | 472            |
| 0.25| 0.25| 0.5 | 1           | 4.55E+12   | 1.06E+08   | 4.70E+07   | 173            |
|    |    |    | 2           | 1.58E+15   | 9.41E+08   | 2.31E+11   | 627            |
| 0.15| 0.15| 0.7 | 1           | 5.59E+12   | 1.16E+08   | 5.67E+07   | 159            |
|    |    |    | 2           | 1.80E+15   | 9.91E+08   | 3.07E+11   | 679            |
| 0.05| 0.05| 0.9 | 1           | 6.20E+12   | 1.25E+08   | 7.02E+07   | 134            |
|    |    |    | 2           | 2.25E+15   | 1.13E+09   | 3.48E+11   | 646            |
| 0.2 | 0.3 | 0.5 | 1           | 5.20E+12   | 9.83E+07   | 4.78E+07   | 164            |
|    |    |    | 2           | 1.68E+15   | 8.90E+08   | 2.25E+11   | 655            |
| 0.2 | 0.5 | 0.3 | 1           | 4.93E+12   | 7.21E+07   | 2.76E+07   | 132            |
|    |    |    | 2           | 1.70E+15   | 6.48E+08   | 1.23E+11   | 690            |
| 0.3 | 0.2 | 0.5 | 1           | 4.38E+12   | 1.13E+08   | 4.63E+07   | 210            |
|    |    |    | 2           | 1.53E+15   | 9.81E+08   | 2.31E+11   | 512            |
| 0.3 | 0.5 | 0.2 | 1           | 4.24E+12   | 6.65E+07   | 1.72E+07   | 167            |
|    |    |    | 2           | 1.53E+15   | 6.38E+08   | 8.61E+10   | 472            |
| 0.5 | 0.2 | 0.3 | 1           | 3.12E+12   | 1.08E+08   | 2.84E+07   | 173            |
|    |    |    | 2           | 9.27E+14   | 9.84E+08   | 1.12E+11   | 627            |
| 0.5 | 0.3 | 0.2 | 1           | 2.93E+12   | 9.59E+07   | 1.79E+07   | 159            |
|    |    |    | 2           | 9.47E+14   | 8.90E+08   | 9.36E+10   | 679            |

for the under study agile SCND problem. The execution time and CPU time on GAMS is very promising and do not exceed than 692 seconds for a large sized problem.

From the optimal values on the Table 9 the same behavior for the second test problem can be depicted as well. Optimal values of $Z_1$ and $Z_2$ (minimization) increase as the weight coefficients of them drops from 0.45 to 0.05, the counter wise behavior is traceable for the third objective function (maximization). As the weight coefficient values increase from 0.1 to 0.9, the optimal values are boosted.

6. Conclusions and future research directions. In this paper, first, PCA approach has been conducted to select a set of the best agile suppliers and then, a multi-objective possibilistic mixed integer non-linear programming (MOPMINLP) model is proposed to cope with the uncertainty in agile SCND problem. The proposed MOPMINLP model is reduced into a MOPMILP model by using mathematical programming techniques. This reduction enables the managers with a wide range of Pareto-solutions with in a reasonable time. The under study agile SCN is
considered to be dynamic and multi-product. The important parameters of the agile SCND problem including customer demand, manufacture costs, transportation costs, fixed costs, holding costs, material costs, integration costs, and delivery time are considered to be uncertain as in real-world problems. To solve the proposed MOPMILP model, an interactive fuzzy solution approach is used. At the end two numerical examples with different sizes are executed to assess the performance of the proposed model. The results show that the proposed approach is capable in designing an efficient agile SCN under uncertainty in a reasonable execution time.

Future research directions can be outlined in two main categories; first is to investigate the proposed model’s capabilities in a case study and implementing it. This direction will need some modifications in the proposed model as every industrial case has its own uniqueness. Second is assessing the applications of exact solution approaches on extra-large problems.

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7. Appendix A. In this section the two Tables mentioned in the text are provided.

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Table 10. The studies mentioning the agility indicators in the literature

| Index | Razmi et al. (2011) | Rahani (2011) | Ghodsi-Pour and O’Brien (1998) | Man and Shin (2008) | Weber et al. (2012) | Dickeson (1999) | Prater et al. (2001) | Kesmez et al. (2014) | Dahmardeh et al. (2010) | Kumar et al. (2011) | Aktepe et al. (1999) | Chan and Thong (2009) | This study |
|-------|---------------------|---------------|--------------------------------|---------------------|---------------------|-------------------|---------------------|---------------------|----------------------|---------------------|---------------------|---------------------|-----------|
| 1     | *                   | *             | *                              | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 2     | *                   | *             | *                              | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 3     | *                   | *             | *                              | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 4     | *                   | *             | *                              | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 5     | *                   | *             | *                              | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 6     | *                   | *             | *                              | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 7     | *                   | *             | *                              | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 8     | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 9     | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 10    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 11    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 12    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 13    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 14    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 15    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 16    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 17    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 18    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 19    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 20    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 21    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 22    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 23    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 24    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 25    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 26    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 27    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 28    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 29    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 30    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 31    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 32    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 33    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 34    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 35    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 36    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 37    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 38    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |
| 39    | *                   |               |                                | *                   | *                   | *                 | *                   | *                   | *                    | *                   | *                   | *                   | *         |

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### Table 11. Agile suppliers attributes

| No. | Int1 | Int2 | Int3 | Int4 | Int5 | Int6 | Int7 | Int8 | Int9 | Int10 | Int11 | Int12 | Int13 | Int14 | Int15 | Int16 |
|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 1   | 0.34 | 0.32 | 0.3  | 0.29 | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 |
| 2   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 3   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 4   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 5   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 6   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 7   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 8   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 9   | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 10  | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 11  | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 12  | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 13  | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 14  | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 15  | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |
| 16  | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.2  | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 |

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E-mail address: azam.moradi@ut.ac.ir
E-mail address: jrazmi@ut.ac.ir
E-mail address: r.babazadeh@urmia.ac.ir
E-mail address: ali_sabbaghnia@ut.ac.ir