A Novel Multi-Objective Fuzzy Mathematical Model for Designing a Sustainable Supply Chain Network Considering Outsourcing Risk under Uncertainty

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Abstract - Industry managers and strategy planners are under rising pressure to continuously develop sustainable supply chain networks that integrate all supply chain decisions and network design is the most basic decision of supply chain management that allows an organization to get the most out of its long-term performance. The design of sustainable supply chain networks has attracted more attention in recent years according to business and environmental factors. In today’s competitive environment the selection of appropriate suppliers is a considerably significant decision for an effective supply chain management. Appropriate suppliers reduce purchasing costs, decrease production lead time and defects, increase customer satisfaction and strengthen corporate competitiveness. This research proposes a bi-objective fuzzy mathematical programming model for designing the strategic configuration of a sustainable supply chain network under uncertain conditions. An original equipment manufacturer that is concerned with minimizing the environmental impact of its activities and risks should design the network based on the trade-off between costs and respective emissions. The negative environmental impact is assessed by measuring CO₂ emission during the manufacturing, remanufacturing and transportations.

Keywords - Sustainable Supply Chain Network; CO₂ Emission; Fuzzy Mathematical Programming; Risk Management

I. INTRODUCTION

Supply chain network design tries to identify the best supply chain design that allows an organization to get the most out of its long-term performance. Supply chain network design is the most basic decision of supply chain management that integrates all supply chain decisions and has the widest effect on the chain’s return on the investment and overall performance. As it is mentioned, supply chain network design is an integrated configuration of supply, manufacturing and demand side sub-systems [1]. Environmental sustainability of the supply chain depends on the purchasing strategy of the supply chain members. Most of the earlier models have focused on cost, quality, lead time, etc. issues but not given enough importance to carbon emissions for the supplier evaluation. Lately, there is a growing pressure on supply chain members for reducing the carbon emission of their supply chain [2].

In modern supply chains material flows could be disrupted by unpredicted natural or man-made disasters such as earthquakes, fires, floods, hurricanes or equipment break downs, labor strikes, economic crisis, bankruptcy or a deliberate sabotage or terrorist attack. All of these disruption events are considered of being low probability—high consequence events that may have a major business shock. Supply chain risk management has been a crucial point for the decision makers in the industry.

The sustainable development is defined as “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” [WCED, 1987]. A lot of research has been done in the literature on supply chain management concerned with environmental issues through the emerging concept green supply chain management. According to the recent comprehensive review on green supply chain management [7], two types of “greensness” are considered by the researchers: green design for products [8] and green operations. Our research falls in the second category which is mainly composed of green manufacturing. However, our research has a different perspective on the “greensness.” More specifically, we are interested in the environmental investment decision making in the network design phase and taking precautions against environmental pollution.

In the last several decades, the topic of supplier selection has had an increasing attention in research
Supplier selection is one of the most significant business decisions faced by purchasing managers in a supply chain. Selecting appropriate suppliers deals with satisfying multi criteria based on price, quality, customer service and delivery [10]. As partnering with the right suppliers has become a key factor to sustain continuing business development, supplier evaluation and selection is increasingly recognized as a strategic and crucial component of supply chain management. The objective of supplier selection is to identify suppliers with the highest potential for meeting a company’s needs consistently [10]. Supplier selection is a multi-criteria problem involving both tangible and intangible criteria, some of which may conflict like low price versus high quality [11]. As it is shown in the related literature, most of the previous works addressing the issue of uncertainty in supply chain network design, apply stochastic programming approaches [12]. The concerned problem is modeled by fuzzy approach because there are two drawbacks using stochastic approach: (1) in various real cases there is not sufficient historical data for uncertain parameters, therefore, we can rarely obtain the actual and exact random distributions of the uncertain parameters. Moreover, the chance constraints elevate significantly the computational complexity of the original problem and (2) in nearly all of previous works on reverse supply chain network design under uncertainty, the uncertainty is modeled through scenario based stochastic programming. In these cases, a large number of scenarios used in representing the uncertainty can lead to computationally challenging problems. As an alternative, fuzzy set theory [13] provides a framework to handle different kind of uncertainty, including fuzzy coefficients for lack of knowledge or epistemic uncertainty as well as flexibility in constraints and goals (e.g., fuzziness), at the same time [14]. The robustness approach is an efficient way to structure uncertainty and make decision in the presence of it. To the best of our knowledge, there is no research work applying the fuzzy optimization approach in the context of robust sustainable supply chain network design considering two different risks.

Resilience strategies aim at obtaining a SCN structure reducing risks and providing capabilities for the efficient implementation of the responsiveness policies previously discussed. This can be done by avoiding or transferring risks [16], and/or by investing in flexible and redundant network structures [17, 18]. Avoidance strategies are used when the risk associated to potential product-markets, suppliers or facility locations is considered unacceptable, due for example to the instability of the associated geographical area.

**II. PROBLEM DISCRIPTION**

The supply network discussed in this paper is of multi-echelon, multi product network type that includes 4 layers: (1) suppliers, (2) Production center (the plant) (3) distribution centers (4) customer zones. As it is shown in Figure 1, through flows the new products manufactured by suppliers and the plant are shipped to distribution centers and then to customers. The production plant has a limited capacity so in order to fill in the customer demands; it purchases the products from suppliers. Normally the suppliers with the lower cost and lower risk (operational and disruption) are the best choices. The suppliers are examined with four specifications, Production and transportation cost, expected defect rate, expected delay rate and CO2 emission (in production process and transportation). As well as the suppliers, these 4 specifications exist in the plant, too. There is a disruption probability for the suppliers and the plant. Due to the contracts with the customers if any disruption, delay or defect occurs, a penalty has to be paid to customers. In order to avoid paying penalties, a prepositioning storing is considered in the network, in which the optimum amounts of products are stored to be used in disruption cases. The storehouse position is in the plant so we there is no transportation cost and it is considered as a safe place. The products would be under a quality test before shipping to customer zone and if there would be any defect, they will be replaced by the storage ones. It is assumed that there would not be any defect in the orders after the final quality test. Distribution capacity should be chosen between the candidate locations with different capacity. The location of customer zones are fixed and predefined and the demand of customers must be fully satisfied without any shortages. Also, we suppose there are multiple capacity levels for establishing production and distribution centers in each location.

To apply the CO2 equivalent index to measure total environmental impact, first, we have followed the Eco-indicator manual guidelines [19]. Following this instruction, the boundary of concerned system and the purpose of environmental impact assessment should be firstly defined. Here, the studied system is a four stage network depicted in Fig. 1, and the purpose is to estimate the environmental impact of concerned network. Secondly, the corresponding life cycle should be defined. In the concerned network, the life cycle stages include production, remanufacturing and transportation from production centers to distribution centers, and transportation from distribution centers to customer zones, from customer zone to collection center and then to recovery centers and finally to the distribution centers. At the third step, the materials and processes being used at each stage of life cycle should be determined and then, at the fourth step, the environmental burden of each material and process should be calculated based on the Eco-indicator database and the equivalent CO2 value. All the above mentioned steps can be implemented simply by using the ECO-it 1.4 software and its database [http://www.pre.nl/eco-it]. This software uses the method developed by the International Panel on Climate Change, called IPCC 2007, to calculate the CO2 equivalent value for each process and material.
The supplies of parts are subject to random local disruptions that are individually related with a particular supplier, terrorist attack, from local natural disasters such as earthquakes, fires, floods, hurricanes, etc. Denote by \( \pi_i \) the local disruption probability for supplier \( i \), i.e., the parts ordered from supplier \( i \) are delivered without disruptions with probability, \((1 - \pi_i)\) or not at all with probability \( \pi_i \). Denote by \( P_s \) the probability that disruption scenario \( s \) is realized, where each scenario \( s \in S \) is comprised of a unique subset \( I_s \subset I \) of suppliers who deliver parts on-time and without any problem, and \( s = \{i, 2, ..., S\} \) is the index set of all scenarios (note that there would be a total of \( s = 2^m \) potential scenarios).

\[
P_s = \prod_{i \in I_s} (1 - \pi_i) \prod_{i \notin I_s} \pi_i \quad \text{if} \quad I_s \neq \emptyset
\]
\[
P_s = \prod_{i \in I_s} \pi_i \quad \text{if} \quad I_s = \emptyset
\]

The producer does not need to pay for ordered and undelivered or delayed parts. However, it is charged with a much higher cost of unfulfilled customer orders for undelivered or delayed parts. However, it is charged with a much higher cost of unfulfilled customer orders for undelivered or delayed parts. However, it is charged with a much higher cost of unfulfilled customer orders for undelivered or delayed parts.

\[w_{ip}^r\] Fixed cost of opening distribution center \( r \) with capacity level \( n \)

\[C_{ij}\] Capacity of supplier \( i \) for producing part \( j \)

\[Q_{lk}\] Capacity of the plant for the part \( j \) with technology \( l \)

\[d_{jk}\] Demand for the part \( j \) and customer zone \( k \)

\[D\] Total demand \( \sum_{j, k} d_{jk} \)

\[e_{jk}\] Per unit shortage cost for the part \( j \) to customer zone \( k \)

\[g_{jk}\] Per unit delay cost for the part \( j \) to customer zone \( k \)

\[p_{ij}\] Per unit price of part \( j \) purchased from \( i \)

\[q_{ij}\] Per unit price of part \( j \) produced in the plant with technology \( l \)

\[A_{ij}\] Expected defect rate of supplier \( i \) in quality of part \( j \)

\[B_{ij}\] Expected delay rate of supplier \( i \) for the part \( j \)

\[\bar{A}_{ij}\] Expected defect rate of the plant for quality of part \( j \)

\[\bar{B}_{ij}\] Expected delay rate of the plant for the part \( j \)

\[\alpha\] Confidence level

\[\bar{\pi}_i\] Disruption probability for supplier \( i \)

\[T_{ij}^p\] Transportation cost for shipping per unit part \( j \) from supplier \( i \) with the mode \( p \)

\[w_{ij}^p\] Transportation cost per unit part \( j \) from production center to distribution center \( r \) with transportation mode \( p \)

\[l_{ijk}\] Transportation cost per unit part \( j \) from distribution center \( r \) to customer zone \( k \) with transportation mode \( p \)

\[\epsilon_{ij}^n\] Capacity level \( n \) for product part \( j \) in distribution centers

\[\epsilon_{ij}^p\] CO₂ equivalent emission per unit product \( j \) shipped from supplier \( i \) with the mode \( p \)
$\hat{L}_{ij}$ CO₂ equivalent emission per unit product $j$ produced by the plant with the technology $l$

$J_{ij}^p$ CO₂ equivalent emission per unit part $j$ shipped from production center to distribution center $r$ by transportation mode $p$

$k_{rjk}^p$ CO₂ equivalent emission per unit part $j$ shipped from distribution center $r$ to customer zone $k$ by transportation mode $p$

ε $j$ Per unit storage cost for part $j$

Variables:

$s_{jls}$ Quantity of products $j$ manufactured at supplier $i$ under disruption scenario $s$

$jls$ Quantity of products $j$ manufactured at the plant with technology $l$ under disruption scenario $s$

$y_{jls}$ Quantity of parts $j$ shipped to distribution center $r$ under disruption scenario $s$

$Z_{rjk}$ Quantity of part $j$ shipped from distribution center $r$ to customer zone $k$ under disruption scenario $s$

$p_{rjk}^s$ = 1 if a distribution center with capacity level $n$ is opened at location $r$, 0 otherwise

$n_{jls}$ Quantity of part $j$ that should be stored under disruption scenario $s$

Model formulation:

Min $\sum_i \sum_j \sum_k p_i \sum_l (\hat{x}_{ijl} + s_{jls} + J_{ij} + y_{jls})$  \hspace{1cm} (1)

Min $\sum_i \sum_j \sum_k \sum_l (\hat{x}_{ijl} + J_{ij} + y_{jls})$  \hspace{1cm} (2)

Subject to:

$\sum_r Z_{rjk} \geq d_{jk}, \hspace{1cm} \forall i, j, s, k,$  \hspace{1cm} (3)

$\sum_l Z_{rjk} \leq \tilde{d}_{jk}, \hspace{1cm} \forall i, j, s,$  \hspace{1cm} (4)

$\sum_l Z_{rjk} \leq \tilde{Q}_{ij}, \hspace{1cm} \forall j, l, s.$  \hspace{1cm} (5)

Objective function (1) minimizes the total cost of purchasing, producing and delay and defect penalties and Objective function (2) minimizes the CO₂ emission of production and transportation through the network. Constraint (3) ensures that the demand of the customer is fully satisfied. Constraint (4) denotes capacity limitations on production in the plant. Constraint (5) ensures that at the orders does not exceed the supplier’s capacities. Also, Constraint (6) declares that the reliability of the preparedness plan against operational disruption must be more than the minimum satisfactory reliability. Constraint (7) indicates that at most one capacity level can be assigned to each distribution center at each candidate location. Constraints (8-9) indicate the flow balance at the centers. Constraint (10) denotes capacity limitations on distribution centers, respectively and also prohibits the units of products being transferred from distribution centers which are not opened. Finally, constraints (11) and (12) enforce the binary and non-negativity restrictions on the corresponding decision variables.

IV. SOLUTION METHODOLOGY AND COMPUTATIONAL RESULTS

In the proposed model, the parameters are fuzzy value in each scenario. Therefore, we could assume that the model for each scenario is a fuzzy programming problem which has to be converted to a crisp model. In order to do so, Jimenez method [20] and TH method [21] is applied for defuzzifying the linear programming problem.
To validate the proposed model, a random test problem based on the normal intervals is created. 3 suppliers, 2 different parts, 3 candidate distribution centers and 4 different customer zones are assumed in the supply chain network. Table I indicates the computational results of the proposed model in the  $\tilde{\Delta}$ level of 0.9.

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According to Table I, the cost and CO2 equivalent minimization objective functions are in conflict with each other as an increase of total CO2 equivalent leads to an increase in total costs and vice versa. Additionally, as the importance weight of the cost minimization objective function is equal to 0.95. On the other hand, more balanced solutions are achieved when $\nu$ varies between 0.8 and 0.05.

V. CONCLUSION

Handling a sustainable supply chain network design problem under uncertain conditions, a new fuzzy mathematical programming model is presented in this paper. The proposed model takes into account both environmental and economic aspects considering operational risk and disruption in the network simultaneously. The CO2 equivalent index is employed to measure the environmental impact of concerned supply chain network. Production technology and transportation mode selection decisions are also integrated with the strategic network design decisions in the proposed model. To cope with the operational risk and disruption, an emergency inventory of parts manufactured by the other suppliers or the plant is considered. The emergency inventory issued to compensate for the loss of capacity of the other suppliers or the plant. To deal with imprecise parameters, the proposed model applies the fuzzy approach, TH and Jimenez methods were used to defuzzify the model. A test problem is also provided to show the practicality of the proposed model as well as the interactive solution approach.

V. REFERENCES