Designing Multi-Echelon Supply Chain Network in the Presence of Conflicting Objectives and Uncertainty

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Abstract: This paper presents a unique multi-objective optimization model for supply chain network design problem considering cost and transportation time minimization as well as customer service level maximization under scenario-based uncertainty with the existence of several alternatives of vehicles to transport the products between facilities, and routing of vehicles from plants to distribution centers (DCs) and DCs to customer zones or customers in a stochastic supply chain system, simultaneously. The objective includes determining the most appropriate transportation channel in terms of selecting suitable vehicles and routes for the second and third echelons of the designed supply chain network. All are done in such a way that network-wide cost and transportation time are minimized and the customer service level is maximized. To solve the model a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) has been used in Matlab 2013a software after careful analysis of different evolutionary algorithms. The model is tested on a randomly generated data set, where a multi-stage supply chain design problem is optimized. By using a new solving method, the model generated a quality set of Pareto-optimal solutions, which can be used by the decision-maker to evaluate different options for designing an efficient supply chain network.

Keywords: Supply Chain Network Design, Multi-objective optimization, Non-dominated Sorting Genetic Algorithm (NSGA-II).

1. Introduction

The supply chain (SC) can be defined as an integrated system or network which synchronizes a series of inter-related business processes to:

- Procure raw materials
- Add value to the raw materials by transforming them into finished/semi-finished goods
- Allocate these products to distribution centers or sell to retailers or directly to the customers
- Expedite the flow of raw materials/finished goods, cash, and information among the various partners which include suppliers, manufacturers, retailers, distributors, and third-party logistics providers

From the above definition, it is comprehensible that there are many independent entities in a supply chain and each of which tries to maximize their inherent objective functions in business transactions. Many of their interests will be conflicting with one another. Thus, a specific scenario giving an optimal design configuration using traditional approaches could be a non-optimal design of the supply chain when we look at the design from a complete system optimization perspective. When conflicting interests occur in a problem, modeling the system using traditional optimization techniques (where there exists one weighted objective function) does not commensurate intuitively with a robust formulation. The results could also be misleading in a dynamic environment which is very realistic. So, the decision-maker should ideally be presented with a vector of Pareto-Optimal solutions (also called efficient solutions), and depending on what his/her intrinsic or priority objective (a particular combination of all objective functions) is, he/she can choose the best design from the efficient set of solutions.

In this paper, the authors developed a tri-objective model that minimizes system-wide costs of the supply chain (fixed costs, variable costs, and transportation costs for different vehicles and routes), transportation time to shift products to customer zones through a particular distribution center, and maximize customer service level for a three echelon supply chain. Picking a set of Pareto front for multi-objective optimization problems require robust and efficient methods that can search an entire space. Therefore, an evolutionary algorithm has been used to find the set of Pareto fronts which have proved to be effective in finding the entire set of Pareto fronts. This work seeks to integrate strategic and operational analysis of a supply chain subject to scenario-based uncertainty.

2. Literature Review

The supply chain may be defined as a network of facilities that performs the procurement of raw material, a transformation of raw materials into end products, and distribution of finished products to retailers or directly to customers. These facilities, which usually belong to different companies, consist of production plants, distribution centers, and retail outlets/customer locations. They are unified in such a way that a modification in any one of them affects the performance of others. A substantial amount of work has been done in the field of optimal SC control. Even though various SC strategies and different aspects of SC management have been explored in the literature, most of the developed models study only quarantined parts of the SC.

Historically, at the earlier stage of supply chain related research, the main concentration of academicians and practitioners was on the design of distribution systems (Canel et al., 2001). Typically, discrete facility location models were projected which possibly encompassed some additional features but that still had a narrow scope and was incapable of dealing with many realistic supply chain requirements. However, in the last decade, noticeable research has been done to increasingly develop more wide-ranging (but tractable) models that can better capture the essence of many supply chain network design (SCND) problems and become a useful tool in the decision-making process. This can be comprehended in the papers by Melo et al. (2006) and Melo et al. (2009) where it also becomes clear that many characteristics of practical relevance in supply chain management (SCM) are still far from being fully assimilated in the models existing in the literature. Designing a distribution network of a supply chain has been viewed as one of the important factors of the total productivity and profitability of the entire SC and can be used to achieve a variety of supply chain objectives. Designing a distribution network consists of three sub-problems, namely, selection of locations, vehicle routing, and inventory control. In the literature, some research studies that amalgamate two of the above sub-problems, such as location-routing problems, inventory-routing problems, and location-inventory problems. Few papers simultaneously studied these three sub-problems of a distribution network. Location-routing problems were surveyed and categorized by Min et al. (1998) and Nagy and Salhi (2007). Inventory-routing problems are studied by Zhao et al. (2008), Yu et al. (2008), and Oppen and Loketangen (2008). Ahmadi and Azad (2010) designed a single objective model for a location routing-inventory problem without considering transportation time and risk-pooling.

The insertion of uncertainty issues in SCND problems is common and has been addressed by many authors (Snyder, 2006). But, Melo et al. (2009) pointed out that the scope of the models that have been proposed is still rather limited due to the natural complication of many stochastic optimization problems. In particular, most of the literature contemplates single-period single-commodity problems. Nevertheless, several papers that address multi-commodity problems in a single-period framework have been identified. This is the case with the problems studied by Guille´n et al. (2005), Listes and Dekker (2005), Sabri and Beamon (2000), and Santoso et al. (2005). These authors studied multiple echelons for designing a supply chain network (SCN). The decision variables were capacity, production or procurement quantity, flow of commodities, and inventory level. Stochasticity is presumed for demand, production costs, and delivery costs, and the objectives cover profit, net revenue, costs, demand satisfaction level, or just the flexibility (regarding the volume or delivery). Hwang (2002) considered a single-product SCND problem with two echelons incorporating location as well as routing decisions and traveling time was stochastic and was assumed to have a known distribution. The central aim was to impose a minimum service level in terms of the number of facilities to establish (to be minimized) and to assure a minimum probability for a customer to be covered which is expressed as a function of the distance and the travel time between the facilities and the customers. Miranda and Garrido (2009) proposed a sequential heuristic approach to optimize inventory service levels in a two-stage supply chain. A single-period single commodity situation was considered.

Most of the literature regarding SCN only considered a single criterion for supply chain planning and optimization, such as cost (Georgiadis et al., 2011; Kopanos et a., 2012), profit (Verderame and Floudas, 2009; Amini and Li, 2011) and net present value (NPV) (Papageorgiou et al., 2001; You et al., 2011). In recent years, multi-objective problems in SCND have been addressed due to advanced computational resources and the development of new methods. One of the earliest papers using a multi-objective method for supply chain by Weber and Current (1993) proposed a multi-objective approach for vendor selection, considering three objectives including the purchasing cost, number of late deliveries, and rejected units. El-Sayed et al. (2010) addressed a single-period multi-commodity supply chain network design problem where uncertainty is assumed for the demand. In addition to the location of the facilities, it is necessary to decide about distribution, production, and inventory. One characteristic that differentiates the problem introduced by Olivares-Benitez et al. (2012) from previous works in the literature was the study of the tradeoff between lead time and cost in the supply chain design, related to transportation choices. The review by Current et al. (1990) made it apparent that the balance of these criteria had not been studied extensively. After that, Arntzen et al. (1995) addressed the supply chain design problem for a company that handled the cost-time tradeoff as a weighted combination in the objective function. The decision variable was the number of products to be sent through each transportation mode available by considering transportation time as the variable to the quantity shipped. The problem was solved using elastic penalties for violating constraints and a row-factorization technique. Zeng (1998) emphasized the importance of the lead time cost tradeoff, associated with the transportation modes available between pairs of nodes in the network, and utilized a mixed-integer programming method to optimize both objectives. Altiparmak et al. (2006) proposed a model with three objective functions to minimize total cost and to minimize the unused capacity of distribution centers as well as to maximize total customer demand satisfied. He handled transportation time as a constraint that determined a set of feasible distribution centers able to deliver the product to the customer before the due date. They formulated a procedure based on a genetic algorithm to obtain a set of non-dominated solutions. Pishvaee et al. (2010) studied a model for a forward/reverse logistics network design to optimize the total cost of the system and the fulfillment of the demand and return rates. Although they considered lead time into their model, similar to Altiparmak et al. (2006), it was considered in the meeting of a due date, and not related to transportation alternatives. They suggested a memetic algorithm to solve this NP-hard problem. Moncayo-Martinez and Zhang (2011) addressed a model similar to that of Graves and Willems (2005) where activities must be selected to design the supply chain aiming to optimize cost and lead time in a multi-echelon network. The decision variable was the selection of the resource for a certain activity in the supply chain by using a Pareto Ant Colony Optimization meta-heuristic. Liao et al. (2011) also studied a multi-objective problem for supply chain design by integrating location and inventory decisions. The objectives were the minimization of cost and the maximization of the fill rate as well as demand fulfilled within a coverage distance with the help of a hybrid of NSGA-II and an assignment heuristic. The lead time was not associated with transportation decisions, but it was implied in the cost of the safety stock. Chaabane et al. (2012) presented a multi-period multi-objective optimization problem where cost and environmental objectives were optimized with a mixed-integer programming model where the selection of transportation modes was considered as a decision variable but not coupled with time. Sadjady and Davoudpour (2012) studied a problem for supply chain design where cost and time were knotted to transportation alternatives. The objective was to optimize a single objective function in which lead time from the transportation alternative was altered into a cost function. The cost objective function was optimized using a Lagrangian relaxation method. According to Wolpert and Macready (1997), there was no single algorithm that can find the best solution for all types of optimization problems, and in the literature, several models have been explored to solve supply chain design problems to get the Pareto optimal solutions. Most of these models were dominated by genetic algorithm and its enhanced versions (Altiparmak et al., 2006; Liao et al., 2011). On top of the genetic algorithm-based supply chain models, several other methods had also been proposed especially based on swarm-based optimization methods (Manham et al., 2009; Che, 2012; Moncayo-Martínez and Zhang, 2013). One of the candid examples of this can be the optimization model designed for a bulldozer supply chain network (Moncayo-Martínez and Zhang, 2011). This model aimed to find the best combination of the resource options by minimizing the total cost and the total lead-time after solving this NP-hard multi-objective problem with the help of the Ant Colony optimization technique. Mastrocinque et al. (2013) proposed a multi-objective model for the same resource options selection problem which has been optimization based on the Bees Algorithm (Pham et al., 2005). The proposed approach showed promising results for explaining and answering the supply chain configuration problem.

In literature, recently, a growing interest has been observed for using evolutionary algorithms to solve multi-objective optimization problems (Dev, 2001; Pinto, 2004; Farahani and Elahipanah, 2008). Different models with different objective functions have been developed where evolutionary algorithms have been successfully used to find Pareto fronts. Sabri and Beamon (2000) addressed an integrated multi-objective supply chain model dedicated to strategic and operational decisions under the certainties of products-delivery and demands. Similarly, Melachrinoudis et al. (2005) had developed a bi-objective supply chain optimization model to minimize cost and maximize service level. Pinto (2004) and Altiparmak et al. (2006) separately proposed solution techniques based on genetic algorithms to find the Pareto optimal solutions for the supply chain network design problems. Farahani and Elahipanah (2008) designed a three echelon single product bi-objective model for the distribution network of a supply chain with the objectives of minimizing costs, backorders, and surpluses of products. The Pareto optimal fonts were originated by using mixed-integer programming to apply non-dominated sorting genetic algorithms.

Though the aim of achieving minimum cost throughout the network and ensuring maximum customer satisfaction level within minimum transportation time is highly correlated, no work yet represents the joint consideration of these three. This gap of the existing literature inspires the authors of this paper to come up with a multi-objectives, multi-echelon, multi-product SCND model under stochastic conditions to minimize cost (fixed cost, variable cost, and transportation cost) and transportation time and to maximize customer service level when different alternatives of vehicles and routes are available.

3. Design of an Integrated SCND Model

The problem considered in this paper is an imaginary situation that can be applied for any generic supply chain network consisting of suppliers $(s \in S)$, plants $(k \in K)$, distribution centers $(j \in J)$, and customer zone/customer $(i \in I)$. Therefore, in general, it's a three echelon multi-product supply chain network in which an arbitrary company produces f sets of products $(f \in F)$ by using r no. of raw materials $(r \in R)$ and tries to achieve maximum customer service level (alternately Demand Fill Rate) within minimum possible transportation time.

In the first echelon, raw materials are purchased from suppliers depending on the minimum cost. In the second echelon, plants transport the finished products to different distribution centers, and finally in the third echelon the DCs transport the products to potential customer zones. Hence, the number and location of plants, DCs, and customers, along with demands and capacities respectively, are fixed and known. The scenario-based uncertainty has been incorporated in the model. A certain known probability has been assigned for determining the likelihood of occurrence of that particular scenario. Under a certain scenario $(n \in N)$ the customer demand, operating cost, and capacity of different suppliers, plants, and DCs are assumed to be known.

Another important point to be noted is that the effect of disruption has also been considered in model formulation. It has been assumed that whenever any disruption $(m \in M)$ occurs or an emergency arises, one supplier becomes unavailable and the amount of raw materials that could have been purchased from that supplier needs to be outsourced at a reasonably higher cost. A known probability has been assigned to represent the likelihood of a supplier becoming unavailable in a disruption or an emergency.

The distribution centers and plants must be selected from a discrete set of potential locations with fixed opening costs and limited capacities. In the second and third echelon transportation channels consist of vehicle types $l \in L$ and $q \in Q$, and routes $v \in V$ and $z \in Z$ respectively and vehicle types and routes are chosen by different selected plants and DCs based on the minimum vehicle and routing cost as well as minimum transportation time. Products from one facility to the other in each echelon of the network are transported by selecting only one type of vehicle among several available alternatives. Each transportation channel represents a type of service with associated cost and time parameters. It was assumed that a faster mode of transportation is usually more expensive.

So, the trade-off between costs, transportation time, and customer service level lead the authors to formulate a mixed-integer tri-objective SCN optimization model. One criterion tries to minimize the fixed cost of selecting suppliers, plants and distribution centers and fixed transportation cost for different vehicles and routes as well as the variable cost of transporting one unit of raw materials from suppliers to plants and one unit of finished products from plant to DCs and DCs to customer zones. The other two criteria cover the transportation time for different vehicles and routes and customer service levels respectively.

3.1 Assumption of the study

Some assumptions have been considered while designing the multi-objective SCN optimization problem. The assumptions of the model are as follows:

i. The structure of the supply chain is fixed
ii. The formulation is a single-period, multi-product model
iii. The operational costs, the customer demand, and the capacity of the facilities are stochastic parameters.
iv. Outsourcing costs are reasonably more expensive than the total average costs per unit product.

v. Scenario-based uncertainty has been incorporated by using a known probability of occurrence of a certain scenario
vi. The probability that a supplier would be unavailable under a disruption/an emergency is known.
vii. Each plant has a limited capacity.
viii. All customers should be served.

The number of available vehicles for each type and the number of allowed routes for each DC is limited. The assumptions about transportation mode and vehicles are as follows:

i. There are several modes of transportation between two consecutive levels.
ii. Between two nodes on an echelon, only one type of vehicle is used.
iii. A faster transportation mode is the more expensive one

To determine all feasible routes, the following assumptions have been used:

i. Each customer should be visited by only one vehicle.
ii. Each route begins at a plant and ends at the same plant for the second echelon and the third echelon, it starts from a DC and ends at the same DC.
iii. Transportation cost for the first echelon will be covered by the supplier and hence selection of transportation channel for the first stage is beyond the capacity of the formulated model in this research.
iv. The sum of the demands of the customers served in each route must not exceed the capacity of the associated vehicle.
v. Each of the distribution center and the vehicle have various limited, and determined capacity

4. Mathematical Modeling

This paper, for the first time, proposed an integrated approach for designing a multi-objective three echelon supply chain network design model under scenario-based uncertainty for the joint optimization of cost, transportation time, and customer service level. The specific objectives of this model are mentioned below:

i. Minimization of cost (Fixed cost, variable cost, fixed transportation cost, and outsourcing cost) designated by W_1
ii. Minimization of transportation time by selecting suitable vehicles and appropriate route from available alternatives designated by W_2
iii. Maximization of customer service level (Demand fill rate) designated by W_3

Before proceeding to the mathematical model, some parameters and variables of the model are introduced in the following:

Parameters

E^{rf} = Amount of raw material ***r*** required in the production of one unit of product ***f***
b_{if}^{n} = Demand of customer zone ***i*** for product ***f*** in scenario ***n***
C_{sk}^{rn} = Fixed cost of providing raw material ***r*** to plant ***k*** by supplier ***s*** in scenario **n**
C_{kj}^{fn} = Fixed cost of providing finished product ***f*** to distribution center ***j*** by plant ***k*** in scenario **n**
C_{ji}^{fn} = Fixed cost of providing finished product ***f*** to customer zone ***i*** by distribution center ***j*** in scenario **n**
B_{sk}^{rn} = Unit cost of providing raw material ***r*** to plant ***k*** by supplier ***s*** in scenario ***n***
B_{kj}^{fn} = Unit cost providing finished product ***f*** to distribution center ***j*** by plant ***k*** in scenario ***n***

B_{ji}^{fn} = Unit cost of providing finished product ***f*** to customer zone ***i*** by distribution center ***j*** in scenario ***n***
d_{sk}^{rmn} = Extra cost for outsourcing one unit of raw material ***r*** under a disruption/an emergency ***m*** when a suppler is unavailable and plant ***k*** is involved in scenario **n**
C_{kjl}^{v} = Fixed transportation cost for transporting any product from plant ***k*** to distribution center ***j*** by vehicle ***l*** by route ***v***
C_{jiq}^{z} = Fixed transportation cost for transporting any product from distribution center ***j*** to customer zone i by vehicle ***q*** by route ***z***
TP_{kjl}^{v} = Transportation time for shifting any product from plant ***k*** to distribution center ***j*** by vehicle ***l*** by route ***v***
TP_{jiq}^{z} = Transportation time for shifting any product from Distribution center ***j*** to customer zone ***i*** by vehicle ***q*** by route ***z***
Q_{sk}^{rn} = Upper limit on the quantity of raw material ***r*** shipped from supplier ***s*** to plant ***k*** in scenario ***n***
Q_{kj}^{fn} = Upper limit on the quantity of finished product ***f*** shipped from plant ***k*** to distribution center ***j*** in scenario ***n***
Q_{ji}^{fn} = Upper limit on the quantity of finished product ***f*** shipped from distribution center ***j*** to customer zone ***i*** in scenario ***n***
P^{n} = Occurrence probability of scenario ***n***
P^{m} = Probability of unavailability of one supplier in a disruption/an emergency ***m***

Continuous Variables

x_{sk}^{r}= Amount of raw material **r** shipped from suppler ***s*** to plant ***k***
x_{kj}^{f}= Amount of finished product ***f*** shipped from plant ***k*** to distribution center ***j***
x_{ji}^{f}= Amount of finished product ***f*** shipped from distribution center ***j*** to customer zone ***i***

Binary Variables

Y_{sk}^{r}= Decision to provide or not to provide raw material ***r*** to plant k by supplier ***s***
Y_{kj}^{f}= Decision to provide or not to provide finished product ***f*** to distribution center ***j*** by plant ***k***
Y_{ji}^{f} = Decision to provide or not to provide finished product ***f*** to customer ***i*** by distribution center ***j***
A_{kjl}= Decision binary variable equal to 1 if vehicle ***l*** is used to transport finished product from plant ***k*** to distribution center j or 0 otherwise
H_{kjv}= Decision binary variable equal to 1 if route v is used to transport finished product from plant ***k*** to distribution center j or 0 otherwise
A_{jiq}= Decision binary variable equal to 1 if vehicle ***q*** is used to transport finished product from distribution center j to customer zone i or 0 otherwise
H_{jiz}= Decision binary variable equal to 1 if route z is used to transport finished product from distribution center j to customer zone i or 0 otherwise

The objective function $\mathbf{W_1}$ minimizes the sum of total fixed cost and expected total variable cost. The fixed cost includes the cost of selecting a particular supplier, plant, and distribution center. Also, it includes fixed transportation costs for certain vehicles and routes as well as the variable cost of shifting one unit of raw material and finished product between facilities and outsourcing cost in case of supplier unavailability. In the last part of the Equation (1), no. of supplier, S, is in the donominator as we are calculating outsourcing cost due to the unavailability of only one supplier. The second objective function $\mathbf{W_2}$ stands for the minimization of the total transportation time for shifting the finished product from plants to customer zones through a particular distribution center. To, minimize transportation time the selection of transportation channels in terms of choosing suitable vehicles and routes has been executed while running the optimization. Finally, the third objective function **W₃** is used for the maximization of customer service level or demand fill rate which has been defined as the ratio of the total amount of finished products delivered to a particular customer to the total amount of finished products demanded by that customer. The formulation is given in the following subsection.

4.1 Mixed-integer Programming Model Formulation

$$\textbf{Minimize } \mathbf{W_1} = \textbf{Fixed Cost} + \textbf{Variable Cost}$$

$$= \left[\sum_n P^n \{\sum_r \sum_s \sum_k C_{sk}^{rn} Y_{sk}^r + \sum_f \sum_k \sum_j C_{kj}^{fn} Y_{kj}^f + \sum_f \sum_j \sum_i C_{ji}^{fn} Y_{ji}^f\} + \sum_k \sum_j \sum_l \sum_v C_{kjl}^v A_{kjl} H_{kjv} + \sum_j \sum_i \sum_q \sum_z C_{jiq}^z A_{jiq} H_{jiz}\right] + \left[\sum_n P^n \left\{\sum_r \sum_s \sum_k B_{sk}^{rn} x_{sk}^r + \sum_f \sum_k \sum_j B_{kj}^{fn} x_{kj}^f + \sum_f \sum_j \sum_i B_{ji}^{fn} x_{ji}^f\right\} + \{\sum_n P^n \sum_m P^m \sum_r \sum_s \sum_k d_{sk}^{rmn} x_{sk}^r\}/\{S\}\right] \quad (1)$$

$$\textbf{Minimize } \mathbf{W_2} = \textbf{Transportation Time}$$

$$= max_j\{max_{k,j,l,v}(TP_{kjl}^v A_{kjl} H_{kjv}) + max_{j,i,q,z}(TP_{jiq}^z A_{jiq} H_{jiz})\} \quad (2)$$

$$\textbf{Maximize } \mathbf{W_3} = \textbf{Service Level}$$

$$= \sum_f \frac{\sum_j \sum_i x_{ji}^f}{\sum_i \sum_n P^n b_{if}^n} \quad (3)$$

Subject to,

$\sum_s x_{sk}^r - \sum_k \sum_j E^{rf} x_{kj}^f = 0$ $\quad \forall r \text{ and } f$ (4)

$\sum_k x_{kj}^f - \sum_i x_{ji}^f = 0$ $\quad \forall f \text{ and } j$ (5)

$\sum_j x_{ji}^f \leq \sum_n P^n b_{if}^n$ $\quad \forall f \text{ and } i$ (6)

$x_{sk}^r - \sum_n P^n Q_{sk}^{rn} Y_{sk}^r \leq 0$ $\quad \forall r, s, \text{and } k$ (7)

$x_{kj}^f - \sum_n P^n Q_{kj}^{fn} Y_{kj}^f \leq 0$ $\quad \forall f, k, \text{and } j$ (8)

$x_{ji}^f - \sum_n P^n Q_{ji}^{fn} Y_{ji}^f \leq 0$ $\quad \forall f, j, \text{and } i$ (9)

$\sum_k \sum_l A_{kjl} \leq \sum_k Y_{kj}^f$ $\quad \forall j \text{ and } f$ (10)

$\sum_j \sum_q A_{jiq} \leq \sum_k Y_{ji}^f$ $\quad \forall i \text{ and } f$ (11)

$\sum_l A_{kjl} \leq 1$ $\quad \forall k, j, \text{and } v$ (12)

$\sum_q A_{jiq} \leq 1$ $\quad \forall j, i, \text{and } z$ (13)

$\sum_v H_{kjv} \leq 1$ $\quad \forall k \text{ and } j$ (14)

$\sum_z H_{jiz} \leq 1$ $\quad \forall j \text{ and } i$ (15)

$Y_{sk}^r, Y_{kj}^f, Y_{ji}^f, A_{kjl}, A_{jiq}, H_{kjv}$, and H_{jiz} are binary variables (16)

$x_{sk}^r, x_{kj}^f, x_{ji}^f \geq 0$ (17)

Equation (4) stands to ensure that the total amount of raw material $\boldsymbol{r}$ shifted to plant $\boldsymbol{k}$ is equal to the required raw materials to produce the total amount of all products made at this plant. Similarly, Equation (5) ensures that all finished products that enter a DC also leave that DC. Equation (6) represents that the total amount of finished products shifted to a customer is less than or equal to the total amount of products demanded by that customer. Equations (7), (8), and (9) ensure that units of a commodity are provided from an origin to destination if and only if the mentioned origin is selected to provide the commodity to the mentioned destination. It has also been ensured that the capacities of different facilities are limited and the amount of material transported from them does not exceed those capacity constraints. Equations (10) and (11) confirms that if a facility (Plant and DC) is selected to provide the product to a particular destination (DC or Customer Zone) only then a vehicle is used to transport product from that selected facility to a particular destination. Equations (12), (13), (14), and (15) stand for the confirmation that if two facilities are related to each other, then a certain type of vehicle transport products between them through a certain route. The vehicle and the route will be chosen depending on the minimum cost and minimum transportation time. Equation (16) represents the binary nature of some variables already defined in the variables section. And, finally, Equation (17) signifies the non-negative nature of the variables.

5. Solution Methodology

For the solution process, a fast and elitist Non-dominated Sorting Genetic Algorithm II (NSGA-II) is used. For that reason, an NSGA-II program in Matlab is used. This program is combining 16 Matlab scripts and 1 Graphic User Interphase (GUI) script that is plotting the results from the generations run.

To use the code, there are necessary adjustments that should be done. These adjustments are not in the scripts themselves but in the way of writing the functions in a Matlab language. While the writing of the code in the traditional linear solvers is intuitive, in this case, there was a need of transforming the formulation model completely in the programming language. Moreover, to understand the behavior of the algorithm, and to test the mathematical model in a coded version, several small problems were run in to define the best settings. Afterward, the following parameters were set:

- The initial population is defined by using uniformly distributed random numbers between the lower and upper bounds. This is done since there is no existing previous optimization data.
- Initial population size: 700
- Maximum number of generations: 200
- Number of objective functions: 3
- Number of variables: 56 integer (Binary) variables, and 24 continuous variables.
- Number of constraints: 60

The code is implemented in Matlab R2013b, on a computer with an i7 processor. Even though the speed was not a problem in the testing of the code, the assessment of the algorithm is out of scope for this research. Rather than doing that, it is used as a novelty in the optimization of supply chain network designs with a triple bottom line approach, where it is aimed for the generation of sufficient quality Pareto-optimal solutions.

5.1 Test Problem Generation

When a testing problem has to be designed, several aspects should be taken into considerations. It has been chosen as an option for designing a test problem specifically suitable for this research, based on a hypothetical supply chain, where the data is conducted by reasonable assumptions.

In particular, it is chosen a three-level supply chain compiled out of two suppliers (S=2), two plants (K=2) for converting two raw materials (R=2) to two final products (F=2) and two distribution centers (J=2), and two customer zones (I=2) to be served. The supply chain problem is assuming the production of two products, where two potential plants can be chosen for its production. As scenario-based uncertainty has been used here, it has been assumed that two different scenarios (N=2) can occur. Also, it has been assumed that two disruptions can happen (M=2). For simplicity, in the test problem, types of vehicles available to transport products from plants to DCs are 2 (L=2), and types of vehicles available to transport products from DCs to customer zones are also 2 (Q=2). No. of routes from plants to DCs is 2 (V=2) and from DCs to customer zone is also 2 (Z=2). The reason for these simplifications is partially explained above, but it lays in the complexity of the mathematical model. Since it is an NP-hard linear problem, it leads to the fact that solving this kind of problem can be a highly delicate procedure, where, not just using evolutionary algorithms should be a standard way, but even developing new ones, or customizing the existing ones might be necessary. However, the testing case can be upgraded in the future, where a more complex supply chain problem can be addressed. The values of the input parameters are given in the following tables (**Table 1** to **Table 8**). However, the developed model will work for any set of input values. P^n = 0.8 and 0.2 for scenario n=1 and n=2 respectively. P^m = 0.5 and 0.7 for disruption m=1 and m=2 respectively.

Table 1: Fixed cost (Money Units, m.u) of selecting supplier s, plant k & DC j for transporting material r to plant k, finished product f to DC j, and finished product f to customer zone i in scenario n

C_{sk}^{rn} (m.u)			C_{kj}^{fn} (m.u)			C_{ji}^{fn} (m.u)		
Notation	Scenario, n=1	Scenario, n=2	Notation	Scenario, n=1	Scenario, n=2	Notation	Scenario, n=1	Scenario, n=2
C_{11}^{1n}	10000	20000	C_{11}^{1n}	20000	40000	C_{11}^{1n}	5000	10000
C_{12}^{1n}	8500	17000	C_{12}^{1n}	16000	32000	C_{12}^{1n}	5500	11000
C_{21}^{1n}	12000	24000	C_{21}^{1n}	12000	24000	C_{21}^{1n}	3500	7000
C_{22}^{1n}	6500	13000	C_{22}^{1n}	14500	29000	C_{22}^{1n}	3000	6000
C_{11}^{2n}	5000	10000	C_{11}^{2n}	18000	36000	C_{11}^{2n}	6000	12000
C_{12}^{2n}	7500	15000	C_{12}^{2n}	19000	38000	C_{12}^{2n}	4500	9000
C_{21}^{2n}	9500	19000	C_{21}^{2n}	20500	41000	C_{21}^{2n}	6500	13000
C_{22}^{2n}	10500	21000	C_{22}^{2n}	15500	31000	C_{22}^{2n}	5500	11000

Table 2: Unit cost of sending raw material r & finished product f from supplier s, plant k & DC j in scenario n

B_{sk}^{rn} (m.u)			B_{kj}^{fn} (m.u)			B_{ji}^{fn} (m.u)		
Notation	Scenario, n=1	Scenario, n=2	Notation	Scenario, n=1	Scenario, n=2	Notation	Scenario, n=1	Scenario, n=2
B_{11}^{1n}	58	29	B_{11}^{1n}	44	22	B_{11}^{1n}	22	11
B_{12}^{1n}	62	31	B_{12}^{1n}	64	32	B_{12}^{1n}	32	16
B_{21}^{1n}	76	38	B_{21}^{1n}	73	37	B_{21}^{1n}	42	21
B_{22}^{1n}	55	28	B_{22}^{1n}	51	26	B_{22}^{1n}	28	28
B_{11}^{2n}	36	18	B_{11}^{2n}	37	19	B_{11}^{2n}	41	19
B_{12}^{2n}	48	24	B_{12}^{2n}	26	13	B_{12}^{2n}	53	27
B_{21}^{2n}	89	45	B_{21}^{2n}	88	44	B_{21}^{2n}	60	45
B_{22}^{2n}	66	33	B_{22}^{2n}	99	50	B_{22}^{2n}	67	50

Table 3: Upper limit on the quantity of raw material r and finished product f shipped from supplier s, plant k and DC j in scenario n

Q_{sk}^{rn}			Q_{kj}^{fn}			Q_{ji}^{fn}		
Notation	Scenario, n=1	Scenario, n=2	Notation	Scenario, n=1	Scenario, n=2	Notation	Scenario, n=1	Scenario, n=2
Q_{11}^{1n}	470	940	Q_{11}^{1n}	115	230	Q_{11}^{1n}	300	600
Q_{12}^{1n}	600	1200	Q_{12}^{1n}	250	500	Q_{12}^{1n}	450	900
Q_{21}^{1n}	350	500	Q_{21}^{1n}	315	630	Q_{21}^{1n}	770	1540
Q_{22}^{1n}	420	840	Q_{22}^{1n}	480	960	Q_{22}^{1n}	530	1060
Q_{11}^{2n}	860	1720	Q_{11}^{2n}	660	1320	Q_{11}^{2n}	940	1880
Q_{12}^{2n}	610	1220	Q_{12}^{2n}	530	1060	Q_{12}^{2n}	680	1360
Q_{21}^{2n}	970	1940	Q_{21}^{2n}	910	1820	Q_{21}^{2n}	850	1700
Q_{22}^{2n}	1050	2100	Q_{22}^{2n}	715	1430	Q_{22}^{2n}	1000	2000

Table 4: Demand of customer zone i for product f in scenario n, b_{if}^{n}

Notation	Scenario, n=1	Scenario, n=2
b_{11}^{n}	10000	20000
b_{12}^{n}	20000	40000
b_{21}^{n}	7000	14000

b_{22}^{n}	25000	50000

Table 5: Amount of raw material r required in the production of one unit of product f, E^{rf} (Same for Scenario 1 and Scenario 2)

Notation	Scenario 1 and 2
E^{11}	2.5
E^{12}	1.5
E^{21}	1
E^{22}	1.5

Table 6: Fixed transportation cost for transporting any product from plant k to DC j and from DC j to customer zone i

Fixed Transportation Cost from Plant k to DC j using Vehicle Type l on Route v, C_{kjl}^{v} (m.u)			Fixed Transportation Cost from DC j to Customer Zone i using Vehicle Type q on Route z, C_{jiq}^{z} (m.u)		
Notation	**Route, v=1**	**Route, v=2**	**Notation**	**Route, z=1**	**Route, z=2**
C_{111}^{v}	7000	6000	C_{111}^{z}	2200	2500
C_{112}^{v}	6300	6800	C_{112}^{z}	1900	2000
C_{121}^{v}	3200	3500	C_{121}^{z}	1700	1500
C_{122}^{v}	3600	3500	C_{122}^{z}	3100	3000
C_{211}^{v}	4700	5000	C_{211}^{z}	3000	2700
C_{212}^{v}	3900	3700	C_{212}^{z}	2100	2500
C_{221}^{v}	6200	6800	C_{221}^{z}	1500	2000
C_{222}^{v}	6800	7500	C_{222}^{z}	2800	2600

Table 7: Transportation time for shifting any product from Plant k to DC j and from DC j to Customer Zone i by different vehicles and different routes

Transportation Time from Plant k to DC j, TP_{kjl}^{v} (hr)			Transportation Time from DC j to Customer Zone i, TP_{jiq}^{z} (hr)		
Notation	**Route, v=1**	**Route, v=2**	**Notation**	**Route, z=1**	**Route, z=2**
TP_{111}^{v}	18	16	TP_{111}^{z}	3	4
TP_{112}^{v}	12	9	TP_{112}^{z}	6	7
TP_{121}^{v}	23	23	TP_{121}^{z}	8	9
TP_{122}^{v}	28	17	TP_{122}^{z}	5	5
TP_{211}^{v}	8	11	TP_{211}^{z}	10	6
TP_{212}^{v}	14	18	TP_{212}^{z}	14	10
TP_{221}^{v}	6	9	TP_{221}^{z}	7	12
TP_{222}^{v}	9	15	TP_{222}^{z}	12	8

Table 8: Extra cost for outsourcing one unit of raw material *r* under a disruption/an emergency *m* when a suppler is blocked and plant *k* is involved, d_{sk}^{rmn}

d_{sk}^{rmn} (m.u)					
Notation	**Scenario n=1**	**Scenario n=2**	**Notation**	**Scenario n=1**	**Scenario n=2**
d_{11}^{11n}	6	4	d_{21}^{11n}	6	4
d_{11}^{12n}	8	7	d_{21}^{12n}	8	7
d_{11}^{21n}	4	6	d_{21}^{21n}	4	6
d_{11}^{22n}	7	5	d_{21}^{22n}	7	7
d_{12}^{11n}	3	6	d_{22}^{11n}	3	5
d_{12}^{12n}	9	7	d_{22}^{12n}	9	8
d_{12}^{21n}	5	8	d_{22}^{21n}	5	3
d_{12}^{22n}	10	6	d_{22}^{22n}	10	8

6. Result Analysis

The results and trade-off analyses are performed at several levels, where various tests with different settings are aiming at answering the research questions. Thus, an overall optimization run is performed for the whole model, afterward a test for the analysis of the cost, transportation time, and at the end an analysis of the customer service level for completing the triple bottom line assessment. On various levels, different types of analysis are conceived, as well as different conclusions provided as an outcome. For the first overall level of analysis, a big optimization cycle was run, with an initial population of 700 and 200 generations.

In addition to the previous discussion, some graphs with the Pareto-Optimal solutions are presented. From **Figures 1 - 6,** it can be seen how the solutions are initiating with a bigger population as highlighted by the figures attached below for lower generations, and afterward are converging towards the most optimal line/surface. Just for clarification, the axis named "objective 3" has negative values due to the coding procedure for maximizing functions in Matlab, but it should be evaluated as a positive number, which represents the customer service level.

On the second level of analysis, the single ranges of the functions were identified. The ranges of the objectives are important, since the decision-maker can seek for solutions that are optimizing at best one particular objective, and according to that can search for complementary solutions.

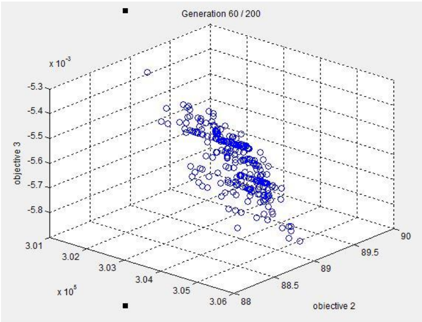

Figure 1: Pareto font of 60th generation

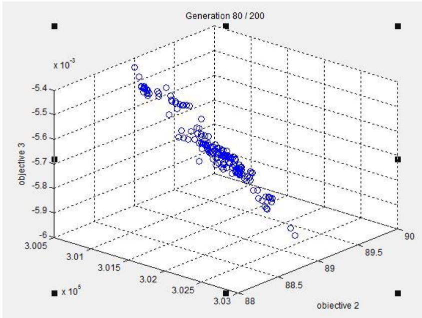

Figure 2: Pareto font of 80th generation

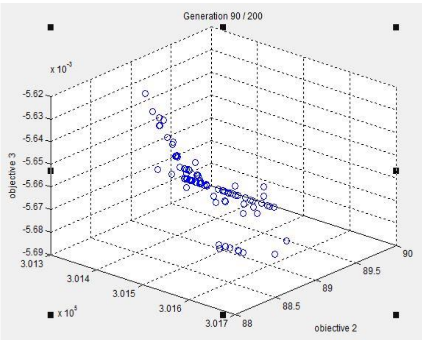

Figure 3: Pareto font of 90th generation

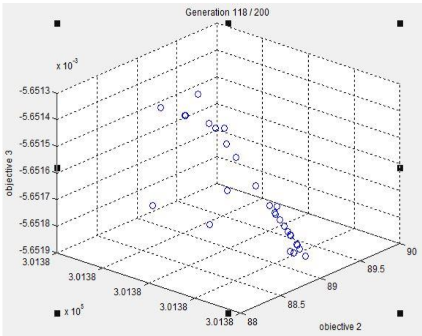

Figure 4: Pareto font of 118th generation

The graph depicts that the minimum value of the cost function is 1,35,685 m.u, and the maximum value is 3,44,475 m.u. Within this band, a lot of values exist with diversified values of decision variables. It should be noted from **Figure 7** that for an appreciable number of solutions of the Pareto font the value of the cost function became stable at the value of approximately 2,50,000 m.u. The decision-maker can select any minimum value within this band for cost function and then the corresponding value of transportation time and customer service level will have to be selected if the decision-maker is interested to give priority to the cost function or in other words wants to set a supply chain network with minimum cost.

In the case of transportation time function, to determine the minimum value of the objective function, it should be observed in **Figure 8** that it is possible to transport any product from any plant to any customer zone through a particular distribution center within 29 hours, which is the minimum. On the other hand, it can take a maximum of 118 hours for the same purpose using a different route.

In both cases, obtaining the minimum and maximum values depend on the selection of the shortest route and fastest vehicle and vice-versa. It is also clear from the **Figure 8** that for a wide range of solutions the value of the time function obtains a stable value of 36 hours. Again, there is the option to make trade-off by selecting any value within this range, and obviously to do that the decision-maker has to choose a different value for each of the other two functions.

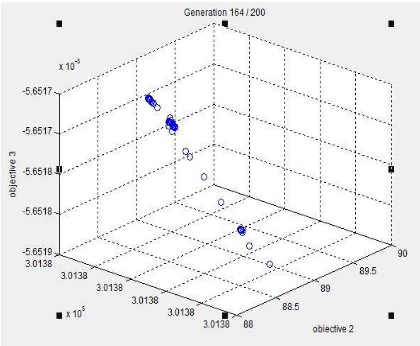

Figure 5: Pareto font of 164th generation

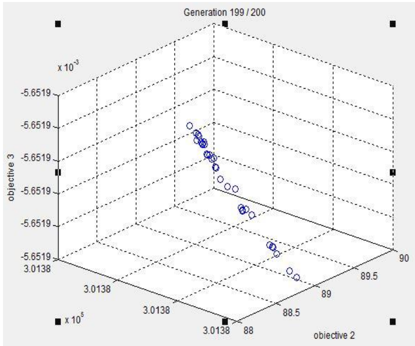

Figure 6: Pareto font of 199th generation

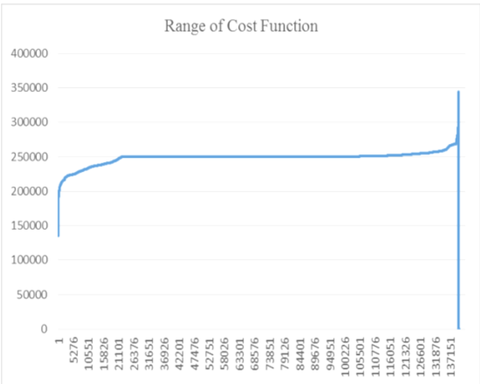

Figure 8: Range of transportation time function

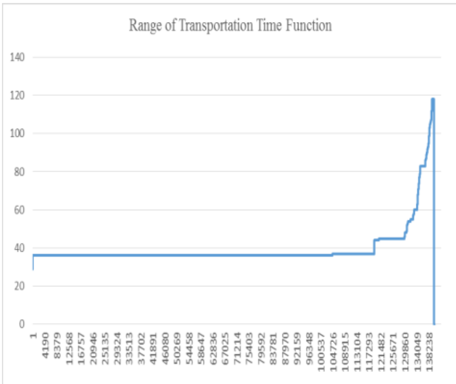

Figure 7: Range of cost function

Unlike the other two objective functions, the aim was to maximize the customer service level. Its conflicting nature influences the value of the other functions while choosing the maximum value of f_3. The graph represents that the decision-maker can select the supply chain network by ensuring the minimum cost and minimum transportation time but at the expense of minimum customer service level with a value of 0.0028235 and 0.944655 in Scenario 1 and Scenario 2 respectively.

On the contrary, the supply chain network can be responsive enough by ensuring the maximum service level of 0.0101824 for scenario 1 and 5.30167 for scenario 2, and to achieve this value there is no doubt that the value of the cost function will be increased. Like the other two functions, there is a wide range within which the value of service level remains stable at the value of approximately 0.004 for scenario 1.

By presenting the character of the objective functions individually, the process of analysis has a basis for continuing and analyzing the conflicted trade-offs between the objectives. This model aims to analyze the interaction between the objective functions and to serve the decision-making process with data that will offer a variety of different solutions.

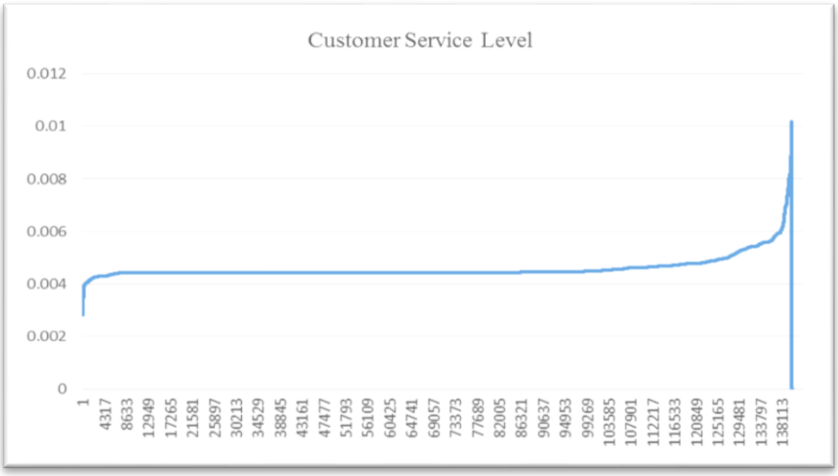

Figure 9: Range of customer service level function

Even though at this stage, the decision-maker should step up with higher-level criteria for selecting solutions, the analysis is proceeding without it. For example, the decision-maker can set the priorities of having the most cost-effective supply chain by ensuring minimum transportation time, while the customer service level can have secondary importance. It can be even chosen the lowest cost solution for selecting a cost-effective supplier and for employing the low-cost vehicle and without paying attention to the customer service level. However, in this case, for the research this kind of data is not necessary, in fact presenting the ability of the optimization has nothing to do with the higher-level criteria. Therefore, out of the non-dominated set of solutions, for the analysis of the multi-objective optimization model, it is decided to pick up the solutions that are giving equal importance to all three of the objectives.

At this stage of analysis, a set of solutions has been elaborated with the value of three objective functions and associated values of 80 decision variables. This solution set has been taken from the Pareto font generated for the 70th generation. The value of the three objective functions are given in **Table 9** and the value of the decision variables are presented in **Table 10**.

Table 9: Value of objective functions for a set of solution

Objective Function	Cost Function	Time Function	Service Level Function* 10000
Values	2,52,529 m.u	36 Hours	45.1904

In **Table 10**, the variables denoted through X_{sk}^{r} to X_{ji}^{f} are designed in such a way that they should represent positive values for the amount of materials that are transported across the supply chain network. The binary decision variables, $Y_{sk}^{r}, Y_{kj}^{f}, Y_{ji}^{f}, A_{kjl}$, H_{kjv}, A_{jiq}, and H_{jiz} are used to select a particular supplier, plant, DC, vehicle, and route. Y_{sk}^{r}, Y_{kj}^{f}, and Y_{ji}^{f} have been defined as binary decision variables to select or not to select different suppliers, plants and DC to transport raw materials or products. A_{kjl} and H_{kjv} have been defined as binary variables to represent the selection of type of vehicle and route from available alternatives for the second echelon of the supply chain (from plant to DC). A_{jiq} and H_{jiz} have been defined as binary variables to represent the selection of type of vehicle and route from available alternatives for the third echelon of the supply chain (from DC to customer zone).

Table 10: Value of the decision variables for particular a set of solution

			$\mathbf{X_{sk}^{r}}$				
X_{11}^{1}	X_{12}^{1}	X_{11}^{2}	X_{12}^{2}	X_{21}^{1}	X_{22}^{1}	X_{21}^{2}	X_{22}^{2}
125.29075	191.21195	106.235	0	268.5815	0	76.3852	157.64435
			$\mathbf{X_{kj}^{f}}$				
X_{11}^{1}	X_{12}^{1}	X_{11}^{2}	X_{12}^{2}	X_{21}^{1}	X_{22}^{1}	X_{21}^{2}	X_{22}^{2}
65.4535	75.3812	27.857	0	6.3662	16.0122	22.8801	67.2972
			$\mathbf{X_{ji}^{f}}$				
X_{11}^{1}	X_{12}^{1}	X_{11}^{2}	X_{12}^{2}	X_{21}^{1}	X_{22}^{1}	X_{21}^{2}	X_{22}^{2}
55.446	16.3737	33.2837	17.4534	91.3934	0	26.5372	40.76
			$\mathbf{Y_{sk}^{r}}$				
Y_{11}^{1}	Y_{12}^{1}	Y_{11}^{2}	Y_{12}^{2}	Y_{21}^{1}	Y_{22}^{1}	Y_{21}^{2}	Y_{22}^{2}
1	1	1	0	1	0	1	1
			$\mathbf{Y_{kj}^{f}}$				
Y_{11}^{1}	Y_{12}^{1}	Y_{11}^{2}	Y_{12}^{2}	Y_{21}^{1}	Y_{22}^{1}	Y_{21}^{2}	Y_{22}^{2}
1	1	1	0	1	1	1	1
			$\mathbf{Y_{ji}^{f}}$				
Y_{11}^{1}	Y_{12}^{1}	Y_{11}^{2}	Y_{12}^{2}	Y_{21}^{1}	Y_{22}^{1}	Y_{21}^{2}	Y_{22}^{2}
1	1	1	1	1	0	1	1
			$\mathbf{A_{kjl}}$				
A_{111}	A_{112}	A_{121}	A_{122}	A_{211}	A_{212}	A_{221}	A_{222}
0	1	0	1	1	0	0	1
			$\mathbf{A_{jiq}}$				
A_{111}	A_{112}	A_{121}	A_{122}	A_{211}	A_{212}	A_{221}	A_{222}
1	0	0	1	0	1	1	0
			$\mathbf{H_{kjv}}$				
H_{111}	H_{112}	H_{121}	H_{122}	H_{211}	H_{212}	H_{221}	H_{222}
0	1	1	0	1	0	1	0
			$\mathbf{H_{jiz}}$				
H_{111}	H_{112}	H_{121}	H_{122}	H_{211}	H_{212}	H_{221}	H_{222}
0	1	1	0	0	1	0	1

In the X^r_{sk} decision variable set, the value of $X^2_{12} = 0$ indicates that no raw material of Type 2 is transported from Supplier 1 to Plant 2. Similar explanations can be given for 0 value of decision variable X^1_{22}. These 0 values are strengthened by the corresponding 0 values of the binary decision variables Y^2_{12} and Y^1_{22} in the Y^r_{sk} decision variables set.

Decision variables X^f_{kj} and X^f_{ji} stand for the amounts of finished product shifted from plant to DC and DC to customer zones respectively. In the X^f_{kj} set, the value of X^2_{12} equal to zero indicates that no finished product of Type 2 is delivered to DC 2 by Plant 1. In the X^f_{ji} set, the value of X^1_{22}= 0 describes that Customer Zone 2 does not receive any amount of finished product of Type 1 from DC 2. The validity of these values is proved by the corresponding 0 values of Y^2_{12}in the Y^f_{kj} set and Y^1_{22} in the Y^f_{ji} set.

$\mathbf{A_{kjl}}$ and $\mathbf{H_{kjv}}$ have been used as binary variables to select or not to select different vehicle types and different routes respectively in the second echelon of the designed supply chain. A_{112} =1 and H_{112}=1 indicate that Vehicle 2 and Route 2 have been used to transport material from Plant 1 to DC 1. Similarly, A_{122}=1 and H_{121}=1 describe that Vehicle 2 and Route 1 have been chosen to transport material from Plant 1 to DC 2. The zero value of some of the above-mentioned variables indicates that the corresponding vehicle type and route are not selected in the second echelon.

Finally, $\mathbf{A_{jiq}}$ and $\mathbf{H_{jiz}}$ have been used as binary variables for selecting transportation channels comprised of vehicle types and routes in the third echelon. A_{111}=1 and H_{112}=1 clarify that Vehicle 1 and Route 2 have been selected to shift product to Customer zone 1 from DC 1. It can also be explained in the same manner for A_{122}=1 and H_{121}=1 i.e Vehicle 2 and Route 1 have been selected for the transportation of product from DC 1 to Customer Zone 2.

Now, three sets of solutions of the reasonable interval for the sake of better realization of the trade-off among three objective function values have been presented in **Table 11**.

Table 11: Comparison of the three solutions

Objective function	Cost Function	Time function	Service Level Function*10000
Solution 1	1,35,685 m.u	76 hrs	67
Solution 2	1,57.421 m.u	56 hrs	50
Solution 3	3,23,111 m.u	102 hrs	80

For solution 1 the value of the cost function is 1,35,685 m.u which is the minimum value of this objective function. At this amount of cost of the network, the minimum transportation time can be as minimum as 76 hrs and the customer service level can be as maximum as 67. The decision-maker can choose this set of solutions if he or she is interested to give priority to the cost function. Now, solution 2 highlights that the transportation time can be minimized to 56 hrs from 76 hrs as it was in the solution 1, but not without sacrificing other two objective function values, since it is clear from the **Table 11** that the value of the cost function increase from 1,35,685 m.u to 1,57,421 m.u and service level reduced to 50 from 67. In the third solution, this is evident that the value of the service level function increased to 80 which is very close to the maximum value of service level for this network. But, to achieve this value reasonably higher cost (3,23,111 m.u) is needed, and for that, the transportation time is also increased to 102 hrs. The reason behind this may be the higher value of the amount of material transported to DC from plant and to customer zones from DCs contributing to the higher value of total transportation cost of the network.

7. Conclusion and Recommendations

This paper addresses a new model for multi-objective optimization of supply chain network design which has the goal of fulfilling and grasping some new research opportunities in the field of supply chain optimization. The model aims to optimize the design of the supply chain network under uncertainty, by selecting the cost-effective suppliers, plants, and DCs. Moreover, the paper also aimed to select the most effective transportation channels for the second and third echelons of the hypothetical supply chain network in terms of choosing suitable vehicle types and routes from available alternatives. During the research, a lot of time has been spent to explore new advanced solving methodologies, which will contribute towards the generation of a better set of Pareto-optimal solutions. Therefore, a new second-generation NSGA-II method is proposed, which is a fast sorting and elitist algorithm, more efficient in sorting the population and guarantees better dispersion of solutions along the frontier. Applying the algorithm is successful, where satisfactory results are obtained. With these, it has opened a new research opportunity for the optimization of sustainable supply chain designs. The applications of this new model can be found in the area of supply chain management and in designing the optimized supply chain network. Besides being a model dedicated to strategic supply chain designs, with certain modifications it can be used for optimizing or restructuring existing supply chains. It is supposed to be an engineering and management tool, rather than being a scientific one. Therefore, global corporations with robust supply chains, who intend to implement effectiveness, efficiency, and responsiveness in the supply chain network can benefit from this research. In the future, a multi-period model can be developed as this is a single-period model. Also, the developed model does not consider in-between stage inventory. Stochastic behavior of input data can also be considered.

8. Funding

This work is funded by Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

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