DESIGN OF INTEGRATED SUPPLY CHAIN NETWORK UNDER TRANSIENT DEMAND AND COST UNCERTAINTY

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Abstract: *A supply chain network is dynamic in nature and is a function of different parameters. This study proposes a mixed integer linear programming model to design a supply chain network considering minimization of total supply chain cost and network flow time along with maximization of demand satisfaction rate and volume flexibility for multiple products and echelons. To reflect the dynamic nature of supply chain, this model addresses transient demand and cost uncertainty. The optimization model provides a set of trade-off solutions between the objectives with facility location decision. The model is illustrated with a simulated example and solved with NSGA-II algorithm to provide a robust solution.*

Keywords: *Supply chain network, Multi-objective optimization, Uncertainty in supply chain, NSGA-II, Pareto optimal solution*

1 Introduction

Now a days, organizations are considering supply chain as an important area which can provide cost effectiveness and competitive edge over similar organizations[1]. Shahparvari et al.[2] define the Supply chain management as, "the coordination and synchronization of the flow of resources in the network of suppliers, manufacturing facilities, distribution centres' and customers". Integration of these stakeholders/ echelons can help achieving profitability and avoid unnecessary events[3]. But the most challenging task is to design an integrated network optimizing all the echelons as they have different and conflicting objectives. Optimizing one of them will not result in maximum overall profitability which can be achieved by considering multiple aspects (i.e. cost, time, customer satisfaction, profit, flexibility etc.) of the supply chain and its dynamic nature[4]. Moreover, the competition between the organizations has been shifted to competition between supply chains. Involvement of multiple entities and multiple level decision making made the supply chain network design (SCND) a multi-objective optimization problem. In a review of facility location problems, Melo et al.[5] indicated that only 9% of the studies consider multiple objectives while 75% of the studies featured solely minimization of cost in Supply Chain Network Design. The objectives like responsiveness, network flow time, lead time, flexibility were not addressed although, several recent studies[3,4,6,7] considered supply chain network design as a multi-objective problem.

In addition to the complexity of SCND, uncertainty in business environment makes supply chain more complex and requires close attention. Usually SCND involves strategic decision making for longer time period but, the initial considerations, constraints, and assumptions change over time[8]. Global economy, climate change, natural disaster, politics etc. anything can change or imbalance the perfect world assumption of supply chain. Moreover, rapid growth of technology is contributing to uncertainty in supply chain. To reflect this dynamic nature, mostly demand uncertainty was considered [9]. Uncertainty in cost, transportation time, supply disruption, labor etc. was paid less of less concern. To create a 'close to real world' model, supply chain network (SCN) should be considered as multi-objective problem with multiple source of uncertainty.

2 Literature Review

Supply chain is driven by a set of parameters, such as, cost, time, flexibility, resilience, service level etc. Different researchers considered different set of parameters in their optimization model, among them cost is the most common. Almost all the literature considers either cost or profit as one of the objectives[3,10–16].

Altiparmak et al.[10] considered cost, service level and capacity utilization in their model. But, they only considered distribution costs and fixed costs in plant and distribution centers. Service level was modelled as the amount of demand satisfied within the acceptable time period. Wang et al.[16] introduced a newer concept, environmental influence, in supply chain modelling. They presented a trade-off approach between cost and environmental effect to assist managerial decision and designing green supply chain. Some researchers[3,17,18] used profit as an objective function instead of cost which is very similar to cost minimization because, profit is calculated by subtracting cost from total revenue and total revenue is constant for deterministic demand models. Another way to represent cost is to evaluate the financial performance of the organization which is adopted in[19].

Other than cost, the most common objective function found in different study is customer satisfaction. Studies in[4,6,20] use demand satisfaction rate/service level which is calculated as the ratio between products sold and existing demand in the market. Another popular objective used in supply chain optimization models is time. Some researchers consider lead time[7,21], some consider network flow time[22] or delay on delivery[11]. Objectives like flexibility, capacity utilization, responsiveness are often left unnoticed but, those are becoming very important as today's supply chain has to deal with a lot of uncertainty.

A good model can become irrational or can produce inaccurate result if the dynamic nature of the supply chain is not reflected. This dynamic nature or uncertainty is now increasing[23]. In a review of supply chain planning under uncertainty, Lalmazloumian and Wong[9] identified three major source of uncertainty. They are, "supply uncertainty, process/manufacturing uncertainty, and demand uncertainty". In their analysis they found that only demand uncertainty was considered in most of the studies. Supply and process/manufacturing uncertainty were mostly ignored[9]. Pujawan et al.[24] also reported three sources of uncertainty - supply, demand, and operations, which they mentioned as causes of instability in scheduling. Lalmazloumian and Wong [9] also categorized different approaches used to address the source of uncertainty. The categories are, Distribution based, Fuzzy based, Scenario based, Simulation based and Hybrid based approaches. Distribution based approach uses stochastic framework to formulate the optimization model wherein Fuzzy based approach use fuzzy set theory. Scenario based approach considers different possible scenarios which helps the organization to prepare for different situations. Simulation based approach use different simulation techniques like discrete event simulation, monte-carlo simulation etc. to internalize the dynamic behaviour and the Hybrid based approach uses a combination of analytic and simulation techniques.

Solving multi-objective SCND problem is a complex one. There are different algorithms, mostly heuristic algorithms used in literature to solve such complex problem. Altiparmak et al.[10,20] used a genetic algorithm approach to solve three objective model wherein Yuce et al.[7] used more advanced, swarm based, and comparatively new bee's algorithm to optimize their two objective model. Ant colony algorithm was used to optimize a three objective supply chain model[4]. Another heuristic based algorithm named as intelligent water drop algorithm was used to optimize bi-objective model in [15]. Each algorithm has its own advantages and disadvantages and there is no specific algorithm which can be efficiently used to optimize all sorts of problem [7]. In the multi-objective supplier selection model, Kazemi et al.[25] used fuzzy approach for solution purposes. In the search for widely used and tested algorithm in supply chain modelling, authors found that Non-dominated Sorting Genetic Algorithm II (NSGA-II) proposed by Deb et al.[26] can perform efficiently and has been used to solve multi-objective supply chain models. Apart from supply chain modelling, this algorithm has been successfully used in chemical process optimization[27] and electricity generation planning [28].

3 Model Formulation

Business world is currently becoming more and more complex because of globalization, intense competition, deregulation, and converging trend of industries[29]. Moreover, rapid development of technology is creating highly variable and quick changing customer demand. To maintain good financial health and competitiveness, an organization should have SCN with optimized cost, time, product quality, flexibility. Our objective is to provide a realistic mathematical model to design a SCN optimized in several front.

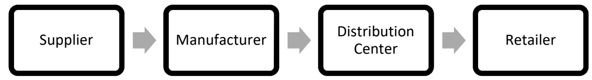
3.1 Problem Identification

A typical supply chain can be defined as an interconnected network between supplier, manufacturer, customer, and distribution network[30]. The optimized network is achieved by selecting optimal resources in order to satisfy organization's specific objective/objectives. Literature shows that supply chain has multi-dimensional characteristics and some of these dimensions are conflicting in nature, such as, higher demand satisfaction rate or service level usually cause higher cost. A better way to resolve these conflicts is to provide a set of trade-off solutions (Pareto Optimal Solution) between the differing objectives.

3.2 Problem Statement

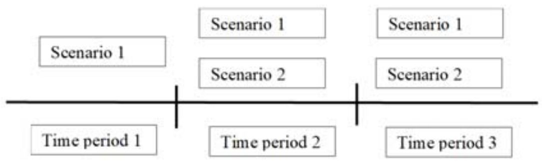
This research considers a generic SCN where manufacturing plant produce multiple products and use warehouses, and distribution centers (DC) to transfer products to customer zones. Therefore, it is a four echelon supply chain network which intends to minimize total cost and network flow time along with maximization of demand satisfaction rate and volume flexibility. An illustration of the echelons is given in the figure bellow.

Figure 1 Arrangement of echelons



Problem in this research assumes that an organization produces multiple products in multiple manufacturing plants. Each plant can produce all types of products. The finished products are then transferred to the warehouse for which the company has different options. It can choose any warehouse from the options depending upon the associated costs (i.e. fixed infrastructure cost, material handling cost and inventory holding cost), capacity, and goal. Then the products are transferred to fixed distribution centers, which will forward the products to different customer zones according to the demands. Demand of each customer zone is assumed to be uncertain. It varies according to time period and possible scenarios (i.e. economic growth or recession, weather, natural disaster, etc.) at each time period. From the historical data, the organization can forecast demand pattern of each product for each time period and scenario. The factors that change the demand pattern will surely impact the cost of production, transportation, material handling, and inventory holding. So, the costs associated with the process are also assumed to be uncertain for different time periods and possible scenarios. Similarly, cost can be estimated from the historical data available from similar situations. Transportation time remains same at different time period and scenario. As it is a universal truth that getting product faster will cost more, transportation costs are assumed higher for those warehouses which take lesser time to transport. The similar case is considered in the transportation of product from warehouse to the distribution center and distribution center to customer zone. Amount of product that can be transported from an echelon to another echelon has certain maximum and minimum value, amount of material transported must fall within this range.

Figure 2 Schematic representation of time period and scenario.



Moreover, parameters that are considered to be uncertain (demand and cost) do not change continuously. It changes after a certain time and remain almost same for a specific period of time. Hence, the uncertainty present in this problem is transient in nature. This study considers three time period based on three seasons in a year (winter, summer, and fall). At the first time period, demand and cost forecast is more accurate than the time period 2 and 3. So, only one possible scenario is considered in time period 1 and two possible scenarios are considered in time period 2 and 3. Number of time period and scenario can be changed for specific organization or fiscal year.

The trade-off between costs, network flow time, demand satisfaction level, and volume flexibility along with transient demand and cost leads the author of this work to formulate a mixed integer multi-objective supply chain network optimization model. One criterion tries to minimize the fixed infrastructure cost of warehouse, production cost, transportation cost in between echelons, material handling costs, and inventory holding cost. Another one tries to minimize total network flow time of a product while the rest two covers the maximization of demand satisfaction level and volume flexibility of the company.

Some assumptions have been considered while designing the multi-objective SCN optimization model. The main assumptions of the provided model are:

1. Work in progress has no holding cost
2. Fixed infrastructure cost does not depend on scenarios as it is a one-time cost.
3. Handling or processing time for a product is same for all warehouses and distribution centers.
4. Material handling cost at manufacturing plant is assumed to be zero.
5. Production rate can vary from scenario to scenario.
6. Each product takes same time to be manufactured at each plant.
7. The structure of the distribution network (i.e. transportation links between plant, warehouse, Distribution center, and customer zone) is independent of the scenarios.
8. Transportation time in between echelons is independent of the scenarios.
9. Each echelon takes same time to handle the material.

3.4 Nomenclature

3.4.1 Indices and Parameters

m = Product types

i = Manufacturing plants

j = Possible warehouse

k = Possible distribution centers

l = Customer zones

s = Possible demand and cost scenarios

t = Time period

C_j^W = Annual fixed cost to establish warehouse *j.*

C_k^D = Annual fixed cost to establish DC at location *k.*

NS = Number of possible scenarios in each time period

Ψ_s = Probability of occurring scenario *s*

C_{mit}^{Ps} = Unit production cost for product *m* in plant *i* during time period *t* under scenario *s*

C_{mjt}^{HWHs} = Unit material handling cost for product *m* in warehouse *j* during time period *t* under scenario *s*

C_{mkt}^{HDCs} = Unit material handling cost for product *m* in DC *k* during time period *t* under scenario *s*

C_{mit}^{IPs} = Inventory holding cost of product *m* at plant *i* during time period *t* under scenario *s*

C_{mjt}^{IWHs} = Inventory holding cost of product *m* at warehouse *j* during time period *t* under scenario *s*

C_{mkt}^{IDCs} = Inventory holding cost of product *m* at DC *k* during time period *t* under scenario *s*

C_{mijt}^{TRs} = Unit transportation cost of product *m* transferred from plant *i* to warehouse *j* during time period *t* under scenario *s*

C_{mjkt}^{TRs} = Unit transportation cost of product *m* transferred from warehouse *j* to DC *k* during time period *t* under scenario *s*

C_{mklt}^{TRs} = Unit transportation cost of product *m* transferred from DC *k* to customer zone *l* during time period *t* under scenario *s*

ΔT_t = Duration of time period *t*

T_{ij} = Transportation time for transferring product from plant *i* to warehouse *j*

T_{jk} = Transportation time for transferring product from warehouse *j* to DC *k*

T_{kl} = Transportation time for transferring product from DC *k* to customer zone *l*

D_{mlt}^{s} = Demand of product *m* from customer zone *l* during time period *t* under scenario *s*

W_j^{max} = Maximum capacity of warehouse *j*

W_j^{min} = Minimum capacity of warehouse *j*

DC_k^{max} = Maximum capacity of DC *k*

DC_k^{min} = Minimum capacity of DC *k*

M_i^{max} = Maximum product holding capacity at plant *i*

M_i^{min} = Minimum product holding capacity at plant *i*

$\alpha_1, \alpha_2, \alpha_3$ = Weight factor for capacity utilization [0, 1]

$Q_{mij}^{s,max}$ = Maximum rate of flow of product *m* that can be transferred from plant *i* to warehouse *j* under scenario *s*

$Q_{mjk}^{s,max}$ = Maximum rate of flow of product *m* that can be transferred from warehouse *j* to DC *k* under scenario *s*

$Q_{mkl}^{s,max}$ = Maximum rate of flow of product *m* that can be transferred from DC *k* to customer zone *l* under scenario *s*

$Q_{ij}^{s,min}$ = Minimum rate of flow of product *m* that can be transferred from plant *i* to warehouse *j* under scenario *s*

$Q_{jk}^{s,min}$ = Minimum rate of flow of product *m* that can be transferred from warehouse *j* to DC *k* under scenario *s*

$Q_{kl}^{s,min}$ = Minimum rate of flow of product *m* that can be transferred from DC *k* to customer zone *l* under scenario *s*

$P_{mit}^{s,max}$ = Maximum production capacity of plant *i* for product *m* at time period *t* under scenario *s*

$P_{mit}^{s,min}$ = Minimum production capacity of plant *i* for product *m* at time period *t* under scenario *s*

3.4.2 Continuous variables

P_{mit}^{s} = Production rate of product *m* for plant *i* during time period *t* under scenario *s*

Q_{mijt}^{s} = Rate of flow of product *m* transferred from plant *i* to warehouse *j* during time period *t* under scenario *s*

Q^{s}_{mjkt} = Rate of flow of product *m* transferred from warehouse *j* to DC *k* during time period *t* under scenario *s*

Q^{s}_{mklt} = Rate of flow of product *m* that can be transferred from DC *k* to customer zone *l* during time period *t* under scenario *s*

I^{s}_{mit} = Inventory level of product *m* being held at plant *i* at the end of time period *t* under scenario *s*

I^{s}_{mjt} = Inventory level of product *m* being held at warehouse *j* at the end of time period *t* under scenario *s*

I^{s}_{mkt} = Inventory level of product *m* being held at DC *k* at the end of time period *t* under scenario *s*

3.4.3 Binary variables

Y_j = 1 if warehouse *j* is established, 0 otherwise.

3.5 Objective function to optimize overall expected cost of supply chain network

Supply chain cost consists of various components. To avoid complexity, researchers often chose a particular set of cost elements. In a research[14], authors considered training, hiring, manpower, and production cost wherein, Altiparmak et al.[10] considered transportation cost and infrastructure cost of manufacturing plant and distribution centers. Sabri and Beamon[31] considered fixed infrastructure cost, transportation cost, and material handling cost. In this model, the cost elements considered by Georgiadis et al.[32] are adopted.

This problem considers warehouse would be established if a potential candidate is chosen. Fixed infrastructure cost of warehouse *j* if it is chosen (when Y_j=1) would be,

$$\sum_j C^{W}_{j} Y_j$$

Production cost of product *m* in produced in plant *i* at time period *t* under scenario *s* can be computed by

$$\sum_{s=1}^{NS} \Psi_s \sum_j C^{Ps}_{mit} P^{s}_{mit} \qquad \forall\, t,\ s = 1, \ldots\ldots\ldots\ldots, NS$$

Material handling cost can be calculated by multiplying the amount of product processed in a warehouse and distribution centers with a fixed rate for time period *t* under scenario *s*.

$$\sum_{s=1}^{NS} \Psi_s \{\sum_{mj} C^{WHs}_{mit} \left(\sum_i Q^{s}_{mijt}\right) + \sum_{mk} C^{DCs}_{mkt} (\sum_j Q^{s}_{mjkt})\} \qquad \forall\, t,\ s = 1,\ldots, NS$$

Inventory holding cost is also calculated in similar manner, cost rate multiplied by inventory on hand. Inventory on hand is calculated by taking the average of on hand product at the beginning and ending of a time period. As we assumed work in progress has no inventory cost, it is not included in this cost element.

$$\sum_{s=1}^{NS} \Psi_s \{\sum_{mi} C^{IPs}_{mijt} \frac{(I^{s}_{mit}+I^{s}_{mi,t-1})}{2} + \sum_{mj} C^{IWHs}_{mjt} \frac{(I^{s}_{mjt}+I^{s}_{mj,t-1})}{2} + \sum_{mk} C^{IDCs}_{mkt} \frac{(I^{s}_{mkt}+I^{s}_{mk,t-1})}{2}\}$$

$$\forall\, t,\ s = 1,\ldots, NS$$

In every time period and scenario, products are transferred from plants to warehouses, warehouses to distribution centers and distribution center to customer zones.

$$\sum_{s=1}^{NS} \Psi_s \left(\sum_{mij} C^{TRs}_{mit} Q^{s}_{mijt} + \sum_{mjk} C^{TRs}_{mjkt} Q^{s}_{mjkt} + \sum_{mkl} C^{TRs}_{mklt} Q^{s}_{mklt}\right)$$

$$\forall\, t,\ s = 1,\ldots, NS$$

Total cost of the supply chain is achieved by taking the summation of all the cost elements mentioned above which leads to the first objective function (f_1).

$$\textbf{minimize } \boldsymbol{f_1} = \sum_j C_j^W Yj + \sum_t \Delta T_t [\sum_{s=1}^{NS} \Psi_s \sum_j C_{mit}^{Ps} P_{mit}^s + \sum_{s=1}^{NS} \Psi_s \left\{ \sum_{mj} C_{mit}^{WHs} \left(\sum_i Q_{mijt}^s \right) + \sum_{mk} C_{mkt}^{DCs} \left(\sum_j Q_{mjkt}^s \right) \right\} + \sum_{s=1}^{NS} \Psi_s \left\{ \sum_{mi} C_{mit}^{IPs} \frac{(I_{mit}^s + I_{mi,t-1}^s)}{2} + \sum_{mj} C_{mjt}^{IWHs} \frac{(I_{mjt}^s + I_{mj,t-1}^s)}{2} + \sum_{mk} C_{mkt}^{IDCs} \frac{(I_{mkt}^s + I_{mk,t-1}^s)}{2} \right\} + \sum_{s=1}^{NS} \Psi_s (\sum_{mij} C_{mijt}^{TRs} Q_{mijt}^s + \sum_{mjk} C_{mjkt}^{TRs} Q_{mjkt}^s + \sum_{mkl} C_{mklt}^{TRs} Q_{mklt}^s)] \quad \dots\dots\dots (1)$$

3.6 Objective function to minimize total network flow time

This model assumes that all the echelons take approximately same amount of time to handle the product, therefore, only transportation time is considered to calculate the network flow time. The target of this objective function (f_2) is to minimize total network flow time.

$$\textbf{minimize } \boldsymbol{f_2} = \sum_t \Delta T_t \left\{ \sum_{s=1}^{NS} \Psi_s \left(\sum_{mij} T_{ij} Q_{mijt}^s + \sum_{mjk} T_{jk} Q_{mjkt}^s + \sum_{mkl} T_{kl} Q_{mklt}^s \right) \right\} \quad \dots\dots \quad (2)$$

3.7 Objective function to maximize demand satisfaction rate

Demand satisfaction rate is the proportion of the demand fulfilled in time period *t* under scenario *s*. Hence, it is calculated by the ratio of product flow from DC to customer zone and demand of customer zone. As the demands are considered weekly demands, it is multiplied by the duration of the time periods in weeks. This objective function (f_3) maximizes the customer demand satisfaction rate.

$$\textbf{maximize } \boldsymbol{f_3} = \sum_t \Delta T_t \sum_{s=1}^{NS} \Psi_s \left(\frac{\sum_{mkl} Q_{mklt}^s}{\sum_{ml} D_{mlt}^s} \right) \quad \dots\dots\dots\dots (3)$$

3.8 Objective function for maximizing volume flexibility

Chod et al.[33] defines volume flexibility as the "ability to change production volume", which can be expressed as the difference between available and utilized capacity. This objective function (f_4) represents the volume flexibility which is the sum of the excess capacity multiplied by a weight factor on each echelon.

$$\textbf{maximize } \boldsymbol{f_4} = \sum_t \Delta T_t \sum_{s=1}^{NS} \Psi_s \{ (\sum_{mi} P_{mit}^s - \sum_{mij} Q_{mijt}^s) \alpha_1 + \left(\sum_j Y_j W_j^{max} - \sum_{mjk} Q_{mjkt}^s \right) + (\sum_k DC_k^{max} - \sum_{mklt} Q_{mklt}^s) \alpha_3 \quad \dots\dots (4)$$

These objective functions (f_1, f_2, f_3, f_4) are subject to the following constraints:

$$Q_{mijt}^s \leq Q_{mij}^{s,max} Y_j \qquad \forall m, i, j, t, s = 1, \dots, NS \quad \dots.(5)$$

$$Q_{mjkt}^s \leq Q_{mjk}^{s,max} Y_j \qquad \forall m, j, k, t, s = 1, \dots, NS \quad (6)$$

$$Q_{mklt}^s \leq Q_{mkl}^{s,max} \qquad \forall m, k, l, t, s = 1, \dots, NS \quad (7)$$

$$Q_{mijt}^s \geq Q_{mij}^{s,min} Y_j \qquad \forall m, i, j, t, s = 1, \dots, NS \quad (8)$$

$$Q_{mjkt}^s \geq Q_{mjk}^{s,min} Y_j \qquad \forall m, j, k, t, s = 1, \dots, NS \quad (9)$$

$$Q_{mklt}^s \geq Q_{mkl}^{s,min} \qquad \forall m, k, l, t, s = 1, \dots, NS \quad (10)$$

$$I_{mit}^{Ps} = I_{mi,t-1} + (P_{mit}^s - \sum_j Q_{mijt}^s) \Delta T \qquad \forall m, i, t, s = 1, \dots, NS \quad (11)$$

$$I_{mjt}^{WHs} = I_{mj,t-1} + (\sum_i Q_{mijt}^s - \sum_k Q_{mjkt}^s) \Delta T \qquad \forall m, j, t, s = 1, \dots, NS \quad (12)$$

$$I_{mkt}^{DCs} = I_{mk,t-1} + (\sum_j Q_{mjkt}^s - \sum_l Q_{mklt}^s) \Delta T \qquad \forall m, k, t, s = 1, \dots, NS \quad (13)$$

$$\sum_k Q_{mklt}^s \leq D_{mlt}^s \qquad \forall m, l, t, s = 1, \dots, NS \quad (14)$$

$$P_{mit}^{s,min} \leq P_{mit}^s \leq P_{mit}^{s,max} \qquad \forall m, i, t, s = 1, \dots, NS \quad (15)$$

$$\sum_m I_{mit}^{Ps} \leq M_i^{max} \qquad \forall i, t, s = 1, \dots, NS \quad (16)$$

$$\sum_m I_{mjt}^{WHs} \leq W_j^{max} Y_j \qquad \forall j, t, s = 1, \dots, NS \quad (17)$$

$$\sum_m I_{mkt}^{DCs} \leq DC_k^{max} \quad \forall k, t, s = 1,\ldots, NS \quad (18)$$

$$P_{mit}^s, I_{mit}^{Ps}, I_{mjt}^{WHs}, I_{mkt}^{DCs}, Q_{mijt}^s, Q_{mjkt}^s, Q_{mklt}^s \geq 0$$
$$\forall m.\, i, t, s = 1,\ldots, NS \quad (19)$$

Equation 5 to 10 represents transportation flow constraints. Material flow from one echelon to another should be within some minimum and maximum value. Equation 11 to 13 ensures the balance of material. Inventory at an echelon at time period t should be equal to summation of inventory on hand at beginning and difference of incoming and outgoing product. Equation 14 is for material balance in customer zone, product transported from distribution centers to customer zone should be less or equal to customer demand. Equation 15 to 18 ensures that the process variables stay within specific capacity limit and equation 19 are to maintain the non-negativity of the process variables.

4 Multi-objective optimization with NSGA-II

The mathematical model formulated in the previous section is a multi-objective model with four objective functions. The solution of this model provides a set of solutions with possible trade-offs between the objectives which is called Pareto Optimal solutions. Researchers use different techniques to solve this kind of problems, i.e. by normalizing the objectives [7], multi-level solution approach [6]. As discussed in the literature, different algorithms were used and among them different versions of Genetic Algorithm were used. For this model, NSGA-II proposed by Deb et al. [34] in would be used. Following section would provide a brief overview of the algorithm.

4.1 NSGA-II: Overview

According to Deb et al.[26], at the t^{th} iteration, a set of population (size = $2N$) is formed by combining two sets of population P_t (parent) and Q_t (children) which are sorted based on no-dominations and provided a rank. The best set of the solutions F_1 is selected for the next iteration. If there is space for more population N, than the next ranked sets $\{F_2,\ldots, F_l\}$ are taken into consideration. $F_1,\ldots, F_l$ creates the new patent set P_{t+1} for next iteration which goes through tournament selection, crossover, and mutation to create the children set Q_{t+1}. The whole process continuous until it reaches to a certain stopping criteria. This algorithm ensures elitism because it considers solutions from both previous string (P_t) and current string (Q_t).

The main strengths of this algorithm, over the others, is the fast sorting of the population, which increases the efficiency, the elitist approach which permits good strings to proceed in the generations and contributes towards better solutions, as well as the better maintaining of the variety of solutions along the Pareto-optimal frontier. Moreover, the simplification of the constraints handling is an additional feature, which permits an easy practical usage. Therefore, the NSGA-II is used as a feasible and satisfactory solving algorithm for obtaining trade-off Pareto-optimal solutions in the following section. The optimality and applicability of the algorithm are discussed after the analysis of the solutions, where a better picture of the performance is available.

5 Illustrative Example

The mathematical model developed in section 3 must be tested for two reasons, to prove the functionality, and to analyze the conflicting outcomes. Therefore, an illustrative example is designed, solved using NSGA-II algorithm, and at the end results from the tests is analyzed. This section is divided into three subsections, namely- i) Design of a Use Case Example and Data population, ii) Solving Method Characteristics, iii) Solution and Analysis.

5.1 Design of a Use Case Example and Data Population

Designing the sample problem began with the search for availability of data, and the possibility of having real business examples. As the real case data was not available, authors were forced to create a hypothetical example. The challenge in working with hypothetical data is to make it close to real life and to make the example close to real life and select the structure of the assumption, authors researched several literature on similar topic. The case study presented by Georgiadis et al.[32] provided a detailed data set which was used as the basis of the assumption. The data population was randomly generated in MS Excel 2013 within an assumed minimum and maximum range. The scenarios are considered equally likely (Probability of a scenario in time period 2 and 3 are 0.50) but, it can be calculated based on historical data.

In particular, it is chosen a four level supply chain compiled out of two plants for converting raw materials to final product, four warehouse options among them any one, two, three, or all can be chosen to satisfy the objectives, three distribution centers (DC) and three customer zones to be served. The supply chain problem is assuming production of a two products, where two potential plants can be chosen for its production. In addition to the lack of real life case, the reason of these simplifications is the mathematical complexity of the model which lays a NP-hard linear problem. All the costs are represented as Relative Money Unit (rmu). All the demands and material flows are represented as tons per week (ton/week). Transportation time is represented in hours.

A part of simulated data population (Production Cost and Demand) is provided in table 1 and 2 as example.

Table 1 Production cost of producing product *m* in plant *i* during time period *t* under scenario *s* (C^{Ps}_{mit}), *rmu/s*

time period t = 1, scenario s = 1		
Product (*m*)	**Plant (*i*)**	
	1	2
1	102	105
2	79	76
time period t = 2, scenario s = 1		
Product (*m*)	**Plant (*i*)**	
	1	2
1	104	101
2	78	76
time period t = 2, scenario s = 2		
Product (*m*)	**Plant (*i*)**	
	1	2
1	105	103
2	81	78
time period t = 3, scenario s = 1		
Product (*m*)	**Plant (*i*)**	
	1	2
1	106	103
2	84	81
time period t = 3, scenario s = 2		
Product (*m*)	**Plant (*i*)**	
	1	2
1	107	104
2	83	84

Table 2 Demand of product *m* from customer zone *l* during time period *t* under scenario *s* (D^{s}_{mlt}), ton/week

time period t = 1, scenario s = 1			
Product (*m*)	**Customer zone (*l*)**		
	1	2	3
1	650	362	521
2	383	506	515
time period t = 2, scenario s = 1			
Product (*m*)	**Customer zone (*l*)**		
	1	2	3
1	507	466	422
2	408	671	455
time period t = 2, scenario s = 2			
Product (*m*)	**Customer zone (*l*)**		
	1	2	3
1	497	659	486
2	533	354	374
time period t = 3, scenario s = 1			
Product (*m*)	**Customer zone (*l*)**		
	1	2	3
1	529	341	498
2	570	467	385
time period t = 3, scenario s = 2			
Product (*m*)	**Customer zone (*l*)**		
	1	2	3
1	589	473	309
2	362	388	442

5.3 Solving Method Characteristics

As mentioned before in section 4, a fast and elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) is used for solution purpose. In order to understand the behavior of the algorithm, the code was run several times with different parameter settings. Afterwards, the following parameters were set:

- Initial population is defined by using uniform distributed random numbers between the lower and upper bounds.
- Initial population size: 700
- Maximum number of generations: 200
- Number of objective functions: 4
- Number of variables: 4 integer (Binary) variables, and 400 continuous variables.
- Number of constraints: 875

The code is implemented in Matlab R2013b, on a personal computer with Intel core i7 processor and 8GB RAM.

5.4 Result analysis

Result was analysed at three levels as various tests was done to answer the research questions. In the process, initial population was set as 700 and termination flag was set at 200th iteration. At the second stage, the range of the objective function and the result of decision variables was analysed. At the last stage, ranges of the objective functions and solutions of 404 decision variables were analysed as it provides vital information to the decision maker about the desired level of the objectives along with number of warehouse established, production rate, material flow, and inventory level for each time period and scenario.

Table 3 Range of Total Supply Chain Cost function

Objective function	Range (*rmu*)	
	Minimum value	Maximum value
Total supply chain cost (f_1)	3077710	4277040

Table 3 and figure 4 depicts that the total supply chain cost varies within the range of 3,077,710 to 4,277,040 rmu. 140,000 solution sets lies within this range with different and spread values of variables. The graph shows that around 4,000,000 rmu, total supply chain cost becomes stable. An appreciable number of Pareto fronts lie in that area. The decision maker can choose any value from this range of costs along with the corresponding values of other objective functions.

The second function is the summation of the required time for all the products to reach in all customer zones for all time periods and scenarios. From this function one cannot tell the specific time duration that a certain product require to reach a certain customer zone at a specific time period under a specific scenario but, one can compare the solution sets and decide which will require lowest time to deliver a product. This function varies from 2,333,080 hours to 3,049,880 hours, represented in table 4 and figure 5.

Figure 4 Range of total supply chain cost

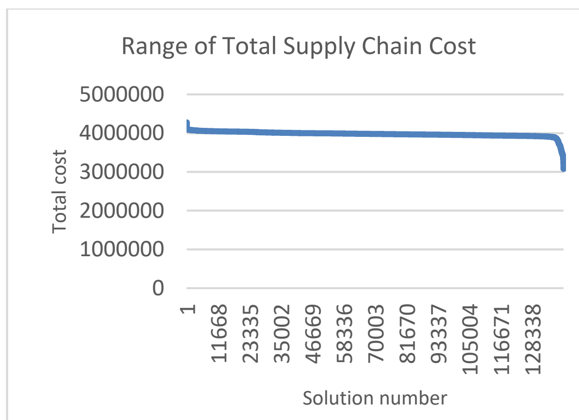


Table 4 Range of Network Flow Time function

Objective function	Range (hour)	
	Minimum value	Maximum value
Total network flow time (f_2)	2,333,080	3,049,880

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 different value of other three functions respectively. If this function is given priority then decision maker can select the solution for which total network flow time is the lowest but, it will cause the cost function to increase.

Figure 5 Range of Network Flow Time

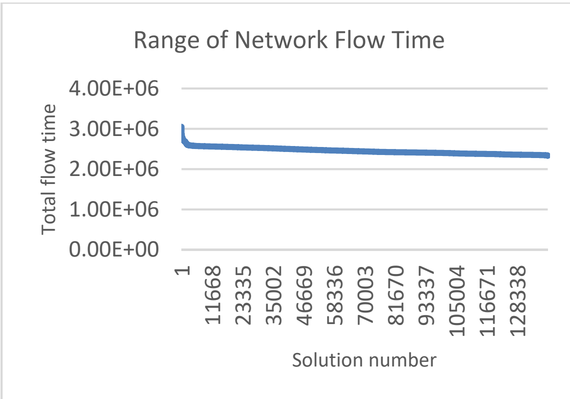
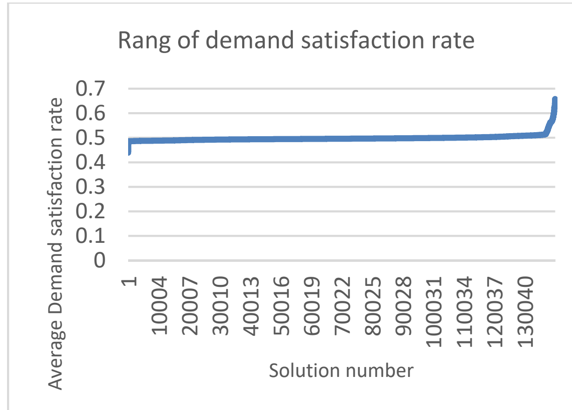


Table 5 Range of Demand satisfaction level function

Objective function	Range	
	Minimum value	Maximum value
Demand satisfaction level (f_3)	47.4507	69.0927
Average Demand satisfaction level for a specific customer zone during a week	0.439358	0.65806

Unlike the previous two objective functions, this function tries to maximize its value. The ranges of this function are presented in table 5. It ranges from 47.4507 to 69.0927. From this value the percentage of demand satisfied cannot be understood because, this objective function value is the summation of the entire weekly demand satisfaction rate for all the customer zones, products and time periods. Further calculation was done *(f_3/ 4 weeks per time period/ 3 time period/ 3 customer zone)* to determine the average demand satisfaction level for each product at each customer zone in a week and their range is 0.439358 to 0.65806, presented in figure 6. That means maximum 66% (approximately) demand can be satisfied for a solution set. Decision maker can select among this range according to business target. As demand satisfaction level increase, cost function will increase surely and there is an option of trade-off for the decision maker.

Figure 6 Range of Demand Satisfaction Level

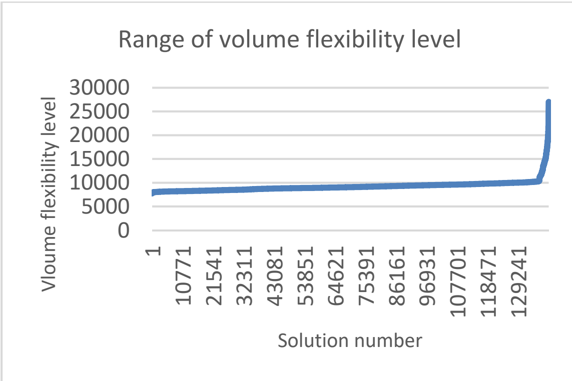


Volume flexibility is the available capacity which can be used to handle the uncertainty. This objective function represents the total volume flexibility for the complete time frame and all the echelons. If average volume flexibility is calculated *{f_4/ 4 weeks per time period/ 5 scenarios/ (2 plants×4 warehouse×3 Distribution center)}* for a plant or warehouse or distribution center, its range will be 16 to 56 (approximately) ton per week. The reason behind very low volume flexibility can be explained by the low demand satisfaction rate. As the organization cannot satisfy all the demands, there would be very low chance of flexibility. For this example, this object seems insignificant as the demand fluctuation is not very high. But, in situations like high demand-low demand scenario, this objective will help significantly in decision making. Decision maker can trade-off the flexibility with the other objective functions according to the situation or policy.

Table 6 Range of Volume Flexibility function

Objective function	Range (ton)	
	Minimum value	Maximum value
Volume Flexibility (f_4)	7770.732	27001.43
Average volume flexibility in each establishment for a week	16.18	56.25

Figure 7 Range of Volume Flexibility



Presenting the characteristic of the objective functions individually, the process of analysis provides a basis for continuing and analysing the conflicted trade-offs between the objectives. Clearly, the aim of this model is to analyse the interaction between the objective functions, and to serve the decision-making process with data that will offer a variety of different solutions. 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 and volume flexibility can have secondary importance. It can be even chosen the lowest cost solution for selecting cost effective options and for employing the low cost warehouse and without paying attention to the customer service level and flexibility. However, for this research that 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 solution, for the analysis of the multi-objective optimization model, it is decided to pick up the solutions that are giving an equal importance to all four of the objectives.

In addition to the previous discussion, some graphs with the Pareto-Optimal solutions are presented. From figures 10 - 14**,** it can be seen how the solutions are initiating with a bigger population as highlighted by the figures attached below for lower generations, and afterwards are converging towards the most optimal line/surface. Objective function 3 and 4 has lower value compared to the objective function 1 and 2. For the purpose of scalarization, objective function 3 and 4 is multiplied by 10^8. Moreover, NSGA-II always minimize the objective functions so, objective function 3 and 4 is represented in invers form. At the last stage of analysis, 404 decision variables has been elaborated one solution set taken from the Pareto front generated at 200th generation and presented in table 7.

Table 7 Value of objective functions for a set of solution

Objective functions	Values
Total supply chain cost (f_1)	4016149.799
Network flow time (f_2)	2348823.428
Demand satisfaction level (f_3)	52.85
Volume flexibility (f_4)	8333.33

The value of four objective functions are given in the table 7 and to acquire these values the decision variables are presented in appendix A with their related values. X1 to X4 are the four binary decision variables used for warehouse selection decision. If any of these variables results 1, then that warehouse is selected for establishment.

Variables X5 to X24 represents the production rate of each product at each plant for all the time periods and possible scenarios. Variable X5 to X14 denotes production rate of product one and X15 to X24 are for production rate of second product in the sequence of time period and scenario.

X25 to X104 has been used to denote the material flow from plant to warehouse. Among these variables, X25 to X64 represent the flow rate of product one from both the plants at time period *t* under scenario *s*. Variables X25, X30, X35 and X40 symbolize the flow rate of product one produced at plant one and transferred to four selected warehouse during time period one and scenario one. Similarly other variables represents production rates of products at different time period and scenarios.

X105 to X224 has been used to represent the flow rate of both the products from warehouses to the distribution centers where X105 to X164 are used for product number one and rest of the variables are used for product number two. X165, X180, X195, X210 represent the flow rate of product one to distribution center one from all the warehouses.

Variable X225 to X314 denotes the product flow rate from distribution centers to customer zones which is driven by demand at different customer zones. X225 to X269 are used for flow rate of product one and among them X225 to X239 are transferred from distribution center one, X240 to X253 represent the flow rate of product one to different customer zones from distribution center two during all three time periods and corresponding scenarios.

Variable X315 to X319 represents the inventory level of product one at plant one, X320 to X324 at plant two. X325 to X329 has been used for inventory level of product two at plant one and X330 to X334 denote inventory level of product two at plant two.

Similarly, variables X335 to X375 represents inventory level of products at different warehouses during all three time periods and corresponding time periods and X375 to X404 has been used to denote inventory level at distribution centers similarly.

The variables represents here represents how much to produce, how much to transport from one specific point to another, how much product should be as inventory in a certain time period and scenario. Moreover, it also shows where and how many warehouses is required to achieve this objective. This model provides a good deal of flexibility as number of products, manufacturing plants, distribution centers, customer zones and warehouse options can be changed to accommodate a specific problem. I addition, establishment of manufacturing plant and distribution center can be considered as decision variables. For this example, we assumed that the supply chain already has two plant and three distribution centers. Instead of that, suitable locations can be considered for the establishment of plants and distribution centers. That will make the model a facility location model for multiple echelon and inclusion of uncertainty will make it very close to real world.

6 Conclusion and Recommendation

The objective of this research was to develop a new supply chain network design model which can help decision making by providing trade-off solutions. After comprehensive literature review research gaps in the field of supply chain network optimization was identified and the objectives for the research design were formed. The proposed model was formulated as MILP model with four objective functions. The objective functions are minimizing total supply chain cost and network flow time along with maximizing demand satisfaction level and volume flexibility considering multi-period demand and cost uncertainty. The model is applied to a hypothetical case example designed to test the functionality of the model and to analyse the result. NSGA-II algorithm was used to solve the model. The model provides a large number of trade-off solutions with corresponding material production, flow, and inventory level for each echelon. Currently this model provides strategic level decision but, with further modification it can be used to provide tactical level decisions. Moreover, it provides facility location decision only for warehouse which can be changed for other echelons.

For future studies, authors recommend considering supplier uncertainty and use of stochastic framework for uncertainty. Moreover, more advanced solution techniques should be explored to achieve better quality solution within shortest possible time.

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