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Mathematical Modelling and a Meta-heuristic for Cross Border Supply Chain Network of Re-configurable Facilities

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Abstract

In supply chain management (SCM), Facility location-allocation problem (FLAP) comes under strategic planning and has been a well-established research area within Operations Research (OR).

Owing to the billion dollar trade between USA-Canada the supply chain costs and difficulties are growing. Binary Integer Linear Programming (BILP) mathematical model is formulated to incorporate several parameters which would optimize the overall supply chain cost. Capacitated, single commodity, multiple time period (dynamic) and multi-facility location allocation problem is considered. Canada being a part of "The Kyoto protocol", a part of the United Nations Framework Convention on Climate Change, has declared to abide by global effort to reduce GHG emissions. Developed math model will include an important constraint to optimize production keeping the Carbon di-oxide gas $[co_2]$ emission levels within specified limits. Simulated annealing based Meta-heuristic is developed to solve the problem to near optimality.

Key Words: Facility Location Allocation, Integer Linear Programming, Simulated Annealing, Border Crossing, Emission

Dedication

Firstly, dedicated to my respected father, Mr. Manohar Hedaoo, who has always been a silent supporter to my entire family.

Secondly, to my mother, Mrs. Madhulika Hedaoo, a creative and strong minded women, who taught me, "Impossible is nothing"

Lastly, to my mentor Maral Zafar Allahyari whose technical guidance proved helpful

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Abbreviations

ILP: Integer Linear Programming

MILP: Mixed Integer Linear Programming

SCND: Supply Chain Network Design

MFLAP: Multiple Facility Location Allocation Problem

SCM: Supply Chain Management

SA: Simulated Annealing

OR: Operation Research

FLAP: Facility Location Allocation Problem

GHG: Greenhouse Gas Emissions

CUSFTA: Canada-U.S. Free Trade Agreement

NAFTA: North American Free Trade Agreement

VRP: Vehicle Routing Problem

FMS: Flexible Manufacturing System

RMS: Re-Configurable Manufacturing Systems

1   Introduction

1.1   Brief Introduction

In supply chain management (SCM), three planning levels are usually distinguished depending on the time horizon. These three levels are strategic, tactical and operational. Strategic level deals with decisions regarding number of facilities, capacity of each facility and the flow of material through the logistics network. Facility location-allocation comes under strategic planning and has been a well-established research area within Operations Research (OR). A facility location allocation problem (FLAP) involves mapping a set of customers to a set of facilities that serve customer demands. Constructing a mathematical linear programming model and a Meta-heuristic algorithm is an efficient approach to optimize supply chain cost. Optimization results allow us to decide quantity of goods to be transported from each facility to its respective customers.

Owing to the billion dollar trade between the USA-Canada the supply chain costs are growing. Trade takes place via cross borders. These borders have disruptions. This problem is incurring high costs to Canadian as well as US manufacturers. To represent this real life problem, an Integer Linear Programming (ILP) mathematical model is formulated. This model incorporates several parameters which would optimize the overall supply chain cost. Capacitated, single commodity, and multiple time period (dynamic), multi-facility location allocation problem is more precise description of the problem under consideration. Canada is a part of "The Kyoto protocol", a United Nations Framework Convention on Climate Change. Canada has declared to abide by global effort to reduce greenhouse gas emissions (GHG) emissions. Due to this, Canadian government is encouraging research to reduce (GHG) emissions. Math model includes an important constraint which allows us to optimize production costs by keeping the Carbon di-oxide $[CO_2]$ emission levels within specified limits. With increasing number of manufacturing facilities and customers over the planning horizon, size of the problem increases. Integer Linear Programming (ILP) mathematical model is in-capable to find solution in limited time and is computationally expensive. To solve large scale problem, simulated annealing meta-heuristic is developed.

1.2   Statistical Background

Since the passage of the Canada-U.S. Free Trade Agreement (CUSFTA) in 1987 and North American Free Trade Agreement (NAFTA), the U.S. and Canada have witnessed explosive growth in trade. Following information obtained from Wikipedia, 2015 explains few details about (CUSFTA):

1. Eliminate barriers to trade in goods and services.
2. Significantly liberalize conditions for investment within free-trade area and facilitate conditions of fair competition.
3. Establish effective procedures for the joint administration of the Agreement and resolution of disputes.
4. Lay the foundation for further bilateral and multilateral cooperation to expand and enhance the benefits of the Agreement.

According to www.naftanow.org, 2013 following are a few details about (NAFTA)

1. It has helped to stimulate economic growth and create higher-paying jobs across North America.
2. It has paved the way for greater market competition and enhanced choice and purchasing power for North American consumers, families, farmers, and businesses.
3. In 2008, Canada and the United States inward foreign direct investment stocks from NAFTA partner countries reached US$469.8 billion.
4. North American employment levels have climbed nearly 23% since 1993, representing a net gain of 39.7 million jobs.
5. The U.S. exports span more than 230 destinations, with Canada and Mexico accounting for more than one-third of the total.
6. If we look at the latest figures at the Canadian side of trade statistics, in the first quarter of the year 2015 a total of 89,321.2 million $ worth merchandise was imported from USA alone and 95,536.9 million $ worth merchandise was exported to USA (www5.statcan.gc.ca, statistics Canada, 2015).
7. Looking at the USA side of trade statistics, in 2013, US goods exports to Canada totaled $300 billion up by 77% from 2003 and goods imports totaled $332 billion. (Office of the United States Trade, 2015).

8. Taking a look at the modes of transportation used for the supply chain, trucks carry three-fifths of U.S.-NAFTA trade and are the most heavily utilized mode for moving goods.

9. Trucks carried 59.9 percent of U.S.-NAFTA trade in May 2014, accounting for $31.8 billion of exports and $30.4 billion of imports.

10. In the year May 2013 to May 2014 trucks carried 53.9 percent of the $57.7 billion of freight to and from Canada.

Considering above figures it can be concluded that huge amount of trade takes place between USA-Canada. Growing trade increases the complexities in supply chain and hence there is great need to design highly efficient supply chain network.

Border delays are generally the first costs cited in most border discussions. Not necessarily because they are the most important costs, but because they are the most visible manifestation of the thickened Canada-US border Anderson (2012). Following table will illustrate and example to show delays (in minutes) at the Ontario-US bridges.

Table 1 Delay times at bridges

	BRIDGE			
STATISTICS	AMBASSADOR	BLUE WATER	PEACE	LEWISTON-QUEENSTON
MEAN	11.3	13.8	13.2	10.8
MEDIAN	7.6	7.5	7.9	5.2
STD .DEV	9.8	18.3	24.6	14.2
MIN	0.8	1	1.1	1
MAX	238.4	288.6	732.1	217.5
OBSERVATIONS	20883	5398	8273	29335

1.3   Motivation

In recent years, a considerable importance is given to the border security problems. The US has initiated a need to "secure" the northern border. Border crossing processes and procedures have received strict attention since 9/11. According to Taylor et al. (2004) causes of border delays and their impacts have been grouped into infrastructure and institutional categories. Highly scrutinized clearance procedures at the USA-Canada border is increasing in-transit inventory holding costs for most manufacturers and suppliers. Further, there is uncertainty in border clearances. Also, there is an uncertainty in time required for crossing USA-Canada border. This has a worst financial impacts on overall supply chain. More specifically, delay- and uncertainty related costs were estimated to total US$4.01 billion Taylor et al. (2004) These costs represent 1.05 percent of total merchandise trade, or 1.58 percent of truck-borne. According to Wigle and Randall (2009) it is estimated that border delays could cost truckers, on an average, about 32 minutes per shipment. This incurs C$290 million per year for Canadian exporters. These additional costs incurred is loss of business, and definitely imply a need for optimization.

Primary causes of delay at USA-Canada border are as follows-:

1. Infrastructure: Number of booths at border crossing in proportion to number of vehicles crossing the border.

2. Human resources: According to the USA homeland security website, amount of staff recruited at USA-Canada border for processing merchandise is not sufficient enough.

Both of these issues are non-technical or related to government administrative policies. Hence, those are beyond our scope of discussion. However, monetary losses associated with the USA-Canada border delays needs to be addressed. To optimize these costs, we have considered to design an efficient supply chain network design.

Following figure gives few causes at the USA-Canada border (Source: TAYLOR et al. (2004)

1. Number of Toll booths

2. Exit check points at the US side

3. Road bed capacity

4. Inspection plazas

5. Processing of line release paper work prior to arrival of carriers not occurring

6. Amount of Staff levels

7. Institutional /Management issues

8. Processing time per vehicle

9. Hours of operation

10. Secondary inspection yards size and availability of parking

1.4   Research Objectives

The primary goal of this thesis is to optimize the overall cost incurred in the USA-Canada cross border supply chain network. Approach to achieve these objectives is to develop ILP mathematical model that will allow deciding the optimal quantities of goods to be produced and shipped by each facility each year. Furthermore, since the model developed is capacitated dynamic facility location allocation, the goal also includes determining the production capacities to be installed at each facility each time period. In a multi-period problem, the customer demand is dynamic and changes over the period of time. Because of customer demand change, the developed model allows dismantling of installed production capacities in order to optimize the production quantity for each facility. Cost component in the developed ILP includes costs associated in construction and dismantling of capacities, domestic and cross border cost of transportation. For determining the optimized production quantities for each facility these supply chain costs associated with corresponding parameters are considered. Additional constraints include limiting the production of each facility such that carbon-di-oxide emissions are maintained within international permissible values.

1.5   Problem and Thesis Statement

"Highly scrutinized clearance procedures at the USA-Canada border is increasing in-transit inventory holding costs resulting in major monetary losses for Canadian exporters. Primarily, to reduce these monetary losses while keeping co_2 emission level within permissible values, we believe that an optimized design of cross border supply chain network is necessary. Designing an Integer Linear Programming model and constructing a meta-heuristic would be an efficient way to achieve the planned objectives."

1.6   Research Approach

An extensive literature review is done to identify which parameters affect supply chain network design. Based on all available parameters, decision variables are chosen. The key decision variables are identified and finalized. These decision variables are discussed in chapter 3 of this thesis. Integer linear programming model is developed. As the size of the problem goes on increasing, it was found that ILP is incapable to give results in less time and is computationally expensive. For example, if number of facilities and customers is high, problem being NP hard, grows exponentially and commercially available optimizing software is unable to reach to optimal solution in finite time. Hence, we develop a simulated annealing based meta-heuristic to obtain near optimal solution.

Stage 1
- To identify relevant parameters, set decision variables, develop objective fuction to optimize cross border supply chain network design between USA-Canada.

Stage 2
- Develop a Binary Integer linear programming model to find-:
- 1. Quantity of goods to be transported between facilities and customers and its corresponding associated cost
- 2. Calculate total cost associated in construction and dismantling of facilities

Stage3
- Develop a Meta heuristic for a large scale problem to find near optimal solution.

Figure 1 : Research Approach

2 Literature review

Supply chain could be defined as a link between various entities of any organization. Supply chain management (SCM) is a strategy through which such integration can be achieved. Supply chain network design (SCND) is a complex undertaking. It involves determining which facilities to include in the supply chain network (e.g., plants, warehouses), their size and location (Correia et al. 2013). Supply chain also establishes the transportation links among the members of the supply chain and setting the flow of materials through them. Supply chain network design problems could be classified under two main categories:

1. Multiple Facility Location Problem (MFLP)

2. Multiple Facility Location Allocation Problem (MFLAP)

In multiple facility location problem the aim is to find optimal location for each facility. Examples include P-median type of problems, capacitated and un-capacitated facility location problem. On the other hand, multiple facility location allocation problem aims at establishing optimum location to a facility. Further, it wishes to determine optimum amount of goods to be transported from a facility to its assigned customer.

Multiple Facility Location Allocation problems are NP hard (Y. Hinojosa et al., 2000). This class of problems address the objective of assigning best location for the facilities, decide which facilities would serve which customer and what should be the optimal quantity to be transported. This gives optimum cost of transportation involved. While assigning facilities to locations new facilities can be set up over the planning horizon. This problem is capacitated, single commodity, multiple facility, and multiple time period location allocation problem. Also,this problem address changing customer demand over the planning horizon. Dynamic location allocation problem aims to answer three important questions. Firstly, which are the best places to locate the available facilities. Secondly, what is the best capacity to assign to the generic logistic facility. Thirdly, at which period of time, what should be the amount of production capacity. Hence, according to Gebennini (2008) "Capacitated, single commodity, multiple facility, and multiple time period (dynamic) facility location allocation problem" will be a complete definition for this class of problem.

2.1   Supply Chain Network Design Literature Review

Isabel Correia , Teresa Melo and Francisco Saldanha-da-Gama (2013) compare classical performance measures for a multi-period, two-echelon supply chain network design problem with sizing decisions. They consider a problem of structural decisions to be made over a multi-period planning horizon as follows:

(i) Selection of new facilities from a given set of candidates

(ii) Facility capacity management through the installation of storage areas for each product family at each open location

(iii) Investment of the available budget for facility location and capacity.

Further decisions concern the quantities of products to be shipped from the upper level facilities to the intermediate level facilities (two echelon), and from the latter to customer zones. Comparison of cost optimization and profit maximization models is done using MILP. However, the linear relaxation bound of the MILP formulation proved to be rather weak in most of the test instances. In particular, solution quality seems to deteriorate as the number of time periods increases.

Ali Amiri (2006) addresses the problem of designing a distribution network for a supply chain system. The goal is to determine the optimum number of plants, optimum locations and optimum assignment of capacities to plants and warehouses. Customer demand is to be satisfied at a minimum total costs of the distribution network. Here, use of multiple level of capacities is done. The author formulates a mixed integer linear programming.

A linear relaxation-based heuristic approach for logistics network design is presented by Thanh et al. (2010). The authors design a multi-period, multi-echelon, multi-commodity logistics network with deterministic demands. This consists of making strategic and tactical decisions like opening, closing or expanding facilities, selecting suppliers, selecting capacity planning and finally defining the product flow. Planning horizon is 5 years. Heuristic approach of successive linear relaxation of the original mixed integer linear problem (MILP) is formulated in this paper. The main benefit of this approach is that it provides a feasible solution of good quality within an affordable computation time. Major drawback is that customer demand is deterministic and certain.

Capacitated dynamic location problems with opening, closure and reopening of facilities is studied by Dias et al. (2006). They include capacitated dynamic location problem that considers

the possibility of reconfiguring one location more than once during the planning horizon. Primal–dual heuristic is developed

Capacity based supply chain network design considering demand uncertainty and using two-stage stochastic programming is different aspect studied by Mishra et al. (2013). Their model also considers inventory carrying cost, opportunity cost in addition to investment cost, processing cost, and transportation cost. The objective of the proposed model is two fold. Firstly,to evaluate optimal locations of echelons and secondly, to determine the quantities flow between them. The objective is to minimize overall cost. However, the model has several assumptions:

1. Probabilities of future economies/market demand is selected at random.

2. Their model does not consider plant capacities as discrete values. Plant capacities are in range. Results of their paper show that few plants have excess capacities assigned ,which contradicts the optimum results.

Multi-level supply chain network design with routing has been studied by Lee et al. (2010). The purpose of their study is to determine the optimal location for facilities, allocation of facilities to customers, and routing for transporting goods. The objective is to design a minimum cost supply chain network. The authors develop a mixed integer programming model for SCND routing. Further, their own heuristic algorithm is developed. The authors conclude that heuristic results are better than MILP results. However, potential drawback in their paper is that there is a maximum capacity restriction.

Optimization models for the dynamic facility location and allocation problem has been studied by Gebennini et al. (2008). The aim of their study is to develop and apply innovative mixed integer programming optimization models to design and manage dynamic (i.e. multi-period) multi-stage and multi-commodity location allocation problems (LAP). They formulate a mixed integer linear programming model. They have applied the model to real life test case. The best solution guarantees a cost reduction of approximately 900000/year. They claim that the proposed model gives solution in less time and do not need to design ad-hoc solving algorithms. However, stochastic demand is not considered in their model. Also, none of the existing facilities are dismantled and constructed again.

A multi period two-echelon multi commodity capacitated plant location problem is studied by Hinojosa et al. (2000). In their model, the capacities of plants and warehouses, as well as

customer demands and transportation costs change over the time periods. They do not consider inventory holding decisions. Goal of their research is to minimize the total cost for meeting customer demands. The customer demand varies for different products over the period of time. Firstly, they develop MILP and then a heuristic. However, from the results it can be confirmed that the computation time is very high for MILP model. Also, once a facility is dismantled it cannot be constructed again. Infeasible solution is obtained when Lagrangean relaxation is used.

An exact method for a two-echelon, single-source, capacitated facility location problem is studied by Tragantalerngsak et al. (2000). In this research paper, the number and location of facilities in two echelons along with the allocation of customers to the second-echelon facilities is to be determined simultaneously. They develop a branch and bound algorithm for a two echelon single source capacitated facility location problem based on the most efficient Lagrangian heuristic. Lagrangian relaxation approach produces significantly smaller B&B trees and consumes much less computing time. However, their approach has a shortcoming in which each customer is serviced by only one facility in the second echelon.

An algorithm for the capacitated, multi-commodity, multi-period facility location problem has been studied Cem Canel et al. (2001). They develop a MILP and then a heuristic algorithm using Bender's decomposition approach. They include a constraints such that the total capacity of open facilities must exceed the total demand of all customers in each period. Drawbacks include that no direct shipment is allowed from facility to customer.

Melkote and Daskin (2001) study capacitated facility location/network design problem. In this problem, authors have combined both facility location and network design which are usually different aspects of supply chain. Facilities have capacity constraint. They develop MILP and LP relaxation using branch and bound. However, they have assumed that customer demand and facility construction cost is normally distributed. Minimum capacity of each facility is assumed equal. They conclude that both link costs and transport costs may actually decrease when capacity constraint is enabled.

A heuristic for the ILP problem like single source capacitated facility location problem has been studied by Guastaroba and Speranza (2014). In their paper, each customer is assigned to a single facility. The objective is to minimize the total cost of opening the facilities and supplying to

all the customers. Kernel search heuristic framework is applied to ILP. They conclude that large size problem can be solved in less time to optimality. However, their problem is not multi-period.

A tabu search heuristic procedure for the capacitated facility location problem is given by Minghe (2012). Three phases like criterion altering, solution reconciling and path relinking are used for the intensification process in the tabu search procedure. The method of Lagrangean relaxation with improved sub-gradient scheme (LRISS) developed by Lorena and Senne (1999) is used as a benchmark to measure the effectiveness and efficiency of the tabu search procedure. They assume that, their heuristic starts the solution process of the current iteration from the optimal solution of the previous iteration.

Arabani and Farahani (2012) present the facility location dynamics overview. They present latest classification of facility location and allocation problems. They also present the mathematical formulations used for each kind of facility location problem.

Some research papers consider inventory optimization. An integrated production distribution model for the dynamic location and allocation problem is considered by authors like Manzini et al. (2009). Additionally, safety stock optimization is achieved in their results. Cost based optimization of supply chain is achieved by integrating strategic, tactical, and operational decision-making. These decisions are related to the design, management, and control of activities. The cost-based and mixed-integer programming model presented has been developed to support management in making decisions like deciding number of facilities (e.g. warehousing systems, distribution centers), choice of locations and assignment of customer demand to facilities. Their paper also incorporates tactical decisions regarding inventory control, production rates, and service-level. Nonlinear objective function is linearized for MILP model. Customer demand is assumed as normal distribution. A major assumption is that all distances are considered as Euclidian distances.

Un-capacitated facility location problem with demand-dependent setup and service costs is considered by Averbakh et al. (2007). The paper gives an insight of some mathematical models which have used un-capacitated facilities. One of the objectives is to choose locations for facilities and balance prices. Other o-bjective is to minimize the expenses of the service company. These expenses include the sum of the total setup costs and total transportation costs. Polynomial time dynamic programming algorithm has been used.

Optimal production allocation and supply chain distribution network design is considered by Tsiakisa and Papageorgiou (2008). The objective of their work is to determine the optimal configuration of a production and distribution network. They include operational and financial constraints in their mathematical model. Their work considers the optimal design and operation of multi-product, multi-echelon global production and distribution networks. The network consists of finding number of existing multi-product manufacturing sites at fixed locations, a number of distribution centers, and finally a number of customer zones at fixed locations using MILP. The best thing about the model is that it aims to assist senior operations management to take decisions regarding production allocation, production capacity per site, purchase of raw materials and network configuration. These decisions take into account financial aspects (exchange rates, duties, etc.) and costs. However, some decisions are already assumed. Decisions such as customer allocation to distribution centers are already defined. Other drawback is that each plant can manufacture a maximum of three products.

A dynamic model for facility location in the design of complex supply chain is presented by Thanha et al. (2008). Their research paper considers multi-period, multi-commodity multi-facility location problem. In their mathematical model all customer demands are deterministic. This research paper aims to help strategic and tactical decision making like opening-closing or enlargement of facilities, supplier selection and determine material flow along the supply chain. However, they have some assumption. Firstly, status of a facility changes only once during the entire planning period. Secondly, closed facilities cannot be reopened while new facilities will remain active until the end of the planning horizon.

Solving complex multi-period location models using simulated annealing is studied by Antunes & Peeter in 2001 .In this paper multi-period location problems raised by school network planning in Portugal is studied. The problem is formulated as mixed-integer linear optimization model. The model allows for facility closure or size reduction. Also, facility opening and size expansion can be done. These expansions are done with sizes possibly limited to a set of pre-defined standards. The study described in this paper shows that simulated annealing may be a good resort when solving complex mid-size multi-period location problems. However, the drawbacks of this paper is that computational time is very high. Also simulated annealing neighborhood solution is accepted with a probability of 10% if it is 30% worse than existing

solution. This decided percentage is problem specific and hence cannot be applied to generic problem.

Solving location allocation problem using rectilinear distances using simulated annealing heuristic algorithm is studied by Chih-Ming Liu et.al (1994). They deal with finding total number of new facilities to be opened, allocation of facilities to customers and the location of the facilities in order to optimize the entire supply chain. For perturbation they are randomly choosing a facility which has not been chosen before and allocating a customer to it. They then calculate the objective function cost and compare it with previous iteration. The authors generate initial solution randomly. They compare their solution with two other heuristics and conclude that simulated annealing heuristic has better solution. Their problem differs from the one considered in this thesis because they are considering rectilinear distances between facilities.

Bi-level simulated annealing algorithm for facility location problem is studied by Ren Peng et.al (2008). Authors have invented Bi-level simulated annealing logics which they call as inner layer simulated annealing logic and outer layer simulated annealing logic. According to which they have decision variables which decide whether to open a facility at location and allocation of the facility to the customer. The outer layer logic decides at which locations facilities should be opened and then it uses add, exchange or remove operator to decide at which locations facilities have to be constructed. The inner layer logic is for optimizing demand allocation. It explains that if a facility is initially allocated to for a customer then using swap operator, the authors generate new combination and calculate objective costs. They conclude that solution is near global optimum and their computation time is also less.

In a private communication, M.F. Baki (2016) mentions the following:

"G. Pandher initiates a research "location problem with border disruption risk" through a grant from the Cross-Border Institute (CBI) at the University of Windsor in 2013. E. Selvarajah collaborates on this research for some time in the beginning. H. Rajput works on this project till November, 2013. In a meeting on December 2, 2013, G. Pandher presented an unpublished note (Author Unknown, 2013) developed through his CBI-grant. The note identifies multiple disruption scenarios that occur on a supply chain network and that's relevant for the facility location decisions. The note develops a single-source binary-integer-program (BIP) facility location model with an additional parameter p_s to represent the probability of disruption s and with an additional

restriction on the maximum number of facilities. The model uses a two-index decision variable x_{ji} which is 1, if customer i is served by facility j and which is 0, otherwise. The model also uses a decision variable y_j which 1, if a facility j is set-up and which is 0, otherwise. The model puts a restriction that every customer must purchase all its demand from a single facility and another restriction on the maximum number of facilities.

M.F Baki presents a model on December 9, 2013 and four more models on January 10, 2014. The models are labelled in an increasing order of complexity and difficulty. Models 1 and 2 are single-sourcing models with 3-index decision variables x_{jis} and Models 3, 4, 5 are capacitated models. Model 1 and all the other models ensure that the sourcing decisions may be different in different scenario, although the facility location decision is the same over all scenarios. Model 1 minimizes the sum of the facility setup cost and the expected production and transportation costs. Model 2 partitions the set of supply chain transportation links into domestic and cross-border subsets E_1 and E_2. The expected costs at the domestic links are affected by the probability of scenario p_s only, but the expected costs at the cross-border links are affected by p_s and e_s, where e_s represents the increase in the cost of scenario s. Model 3 introduces fixed capacity of facilities, capacity additions and dismantling. Model 4 gives a different sourcing decision in a different time period. Model 5 gives a different sourcing decision for a different product. Out of these 5 models, Model 2 is used without modification in (Pandher and Baki, 2015) and Model 4 is extended significantly in this thesis."

Pandher and Baki (2015) developed expected cost of disruption which is a function of the length and frequency of disruption. Similarly they formulate a novel function called "critical cost of disruption". If expected cost of disruption exceeds the critical cost of disruption, the optimal location decision changes from one supply facility on one side of the border to two supply facilities on two sides of the border. To describe their linear programming model, they have given a small example in which they conduct break even analysis for deciding the construction of facilities at two possible locations. They prove that if the expected cost of disruption is greater than critical cost of disruption the optimal location decision changes. Further, they discuss the effect of increase in cost due to increase in length and frequency of disruption. Additionally, they study the effect of population / size of demand by comparing the critical cost function of two demand locations.

Research paper has also been studied. According to ReVelle and Swain (1970) research in which the authors have introduced a p-median problem.

Objective function is to minimize

$$\sum_{j \in J} \sum_{i \in I} p_i d_{i,j} y_{j,i}$$

Constraints:

$\sum_{j \in J} y_{j,i} = 1$	$\forall\, i\, \in I$	(1)
$y_{j,i} \leq\ x_j$	$\forall\, i\, \in I\,, j \in J$	(2)
$\sum_{j \in J} x_j = p$		(3)

$d_{i,j}$ is distance and p_i is the customer demand. Constraint (1) ensures that customer demand is satisfied completely by a single facility. Constraint (2) tells that if a facility is not constructed then it cannot supply to customer. Constraint (3) total number of built DCs should be equal to specified number.

Hoda A. ElMaraghy (2006) writes a paper of Fexible and reconfigurable manufacturing systems paradigms. In this paper she mentions that RMS promises customized flexibility on demand in a short time, while Flexible Manufacturing System (FMS) provides generalized flexibility designed for the anticipated variations and built-in a priori. The key feature of RMS is that, unlike FMS, its capacity and functionality are not fixed (Mehrabi et al., 2000). ElMaraghy further mentions the key definitions of RMS and FMS. As per the author, RMS is designed at the outset for a possible rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family. An FMS is a system whose machines are able to perform operations on a random sequence of parts of different types with little or no time or other expenditure for changeover.

"Mechanics of Change: A framework to reconfigure manufacturing systems" by Azab et al. (2013) describes manufacturing system reconfiguration as a controller, which minimizes the deviation between current values of re configurability and sustainability metrics and their reference values.

Their aim is to design adjustable reconfigurable solutions to minimize the cost while aligning the change requirements with the system performance measure. For that they introduce a control loop approach for change synchronization. The author also gives detail explanation on system level and machine level reconfiguration methodologies.

"A Reconfigurable Manufacturing System (RMS) is one designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements" Koren et al.(1999) The concept of a RMS designed specifically for scalability was first introduced by Spicer et al.(2002). This concept, called scalable-RMS, provides the option of adding and removing multiple identical modules.

"A reconfigurable manufacturing system (RMS) that is designed specifically to adapt to changes in production capacity, through system reconfiguration, is called a scalable-reconfigurable manufacturing system" Spicer and Carlo (2007). This definition allows us to derive a relation that a manufacturing facility can be reconfigurable and the system installed in it can be made scalable. Hence, we can say that scalability is an attribute of reconfigurable manufacturing facility.

"With reconfigurable manufacturing systems on the other hand, capacity scalability addresses the reduction of capacity besides the expansion." Deif and ElMaraghy (2006).

Wilhelm et al. (2013) discuss the computational comparison of two formulations for dynamic supply chain reconfiguration with capacity expansion and contraction. Their problem is to prescribe the location and capacity of each facility, select links used for transportation, and plan material flows through the supply chain, including production, inventory, backorder, and out sourcing levels. Research objectives of this paper area traditional formulation and a network-based model of the problem. Their paper clearly defines concept of a "reconfigurable manufacturing facility" in terms of a facility location allocation problem. This paper is used to benchmark and develop the title of our thesis.

Facility Location Problem for Reconfigurable Manufacturing System (RMS) with Changing Multi-Period Demand is the title of the research paper written by Jeong and Seo (2008). Short product life-cycles and varied customer demands result in use of reconfigurable manufacturing systems by all the growing companies. This paper aims to determine the period of reconfiguration and an

operation plan for Reconfigurable Manufacturing System, and material flow quantity between facilities in a supply chain network. In their paper, they focus on FLP in which RMS, Distribution centers and retailer are facilities of SCN. Reconfigurable Manufacturing System produces the products, Distribution centers distributes the products from RMS to retailers, and retailer meets customer demands. Hence the manufacturing facility having a Reconfigurable Manufacturing System (RMS) is termed as a reconfigurable facility. This paper is thus referred in for defining the relation between RMS and how a facility can be considered as a reconfigurable.

2.2   Emission Literature Review

When an organization becomes multinational it acquires customers across various countries. To supply its customers, it establishes global supply chain network. With the growing demand across the globe, size of supply chain also increases exponentially. With every route added in supply chain there is an increase in mode of transportation which is inevitable. Due to this ever increasing number of vehicles there is a tremendous increase in the carbon dioxide emission. These vehicles burn fossil fuels. Thus, some leading companies are now proactively implementing "green" initiatives. For example, the largest furniture manufacturer, IEKA, built a train transportation network with an emphasis on the "greenness" of train operations. HP, IBM, and GE are all taking "green" as an important merit in their enterprise's value systems in order to maintain good public image. They are designing greener products by adopting new energy saving technology Wang et al. (2010). The temperature of the earth has increased by 0.8 degrees Celsius between 1900 and 2005. Freight transport in the United Kingdom is responsible for 21% of the carbon-di-oxide emissions from the transport sector, amounting to 33.7 million tons or 6% of the carbon-di-oxide emissions in the country. Out of the total, road transport accounts for a proportion of 92% (McKinnon, 2007). Similar figures apply to the United States, where the percentage of total GHG emissions due to transportation rose from 24.9% to 27.3% between 1990 and 2005. Road transport alone accounts for 78% of the emission produced by all transportation modes (Ohnishi, 2008). There are number of active carbon markets for GHG emissions such as the European Union Emission Trading Scheme (EU ETS) in Europe. This is the largest multi-national GHG emissions trading scheme in the world. Few other carbon trading markets include New Zealand Emissions Trading Scheme (NZ ETS) in New Zealand, Chicago Climate Exchange in the

United States and more recently the Montreal Climate Exchange in Canada. According to Chaabane et al. (2010) GHG emissions are calculated based on emission factors and are converted to carbon dioxide equivalent quantity. Diabat and Simchi-Levi (2009) explain details about kyoto protocol. Kyoto protocol, a part of the United Nations Framework Convention on Climate Change, was negotiated as a part of global effort to reduce GHG emissions. The protocol establishes legally binding commitments on all member nations to reduce their GHG emissions. The working of Kyoto protocol is as follows:

1. Every member country government establishes a limit on total emission in fixed duration of time.

2. To achieve its emission targets government sets carbon emission restrictions on each industry and encourages them to use green technologies so as to reduce pollution.

3. Every industry receives fixed amount of carbon credits at beginning of planning horizon. Each carbon credit permits 1 Ton carbon dioxide emission in the atmosphere.

4. Once the company uses its credits it can buy more credits at some price from the government or from the companies which have excess credits left. This is called carbon trading. By this way every company or organization tends to save more credits and eventually money by turning towards green operational technologies.

5. Additionally, if the company is able to achieve its emission targets, it gets economic incentives from governments.

Green logistics has recently received increasing and close attention from governments and business organizations. The importance of green logistics is motivated by the fact that current production and distribution logistics strategies are not sustainable in the long term. Thus environmental, ecological and social effects are taken into consideration when designing logistics policies. Additionally, conventional economic costs are also considered. The environmentally sensitive logistic policy requires changing the transportation scheme. Such policy will have fewer negative impacts on the environment and the ecology. This is because transportation accounts for the major part of logistics. There is a wide variety of problems concerning green transportation, such as the promotion of alternative fuels, next-generation electronic vehicles, green intelligent transportation systems, and other eco-friendly infrastructures. According to Canhong Lin (2014) better utilization of vehicles and a cost effective vehicle routing solution would directly achieve sustainable transportation schemes.

A multi-objective optimization model for green supply chain network design is studied by Wang et al. (2010). They try to achieve trade-off between the total cost and the environment influence. However, if the emission per facility is to be considered then they haven't considered demand uncertainty.

Routing is considered by Bektas and Laporte (2011). They study which route has to be considered so as to optimize those not just for the travel distance, but also for the amount of greenhouse emissions, fuel, travel times and their costs. Managerial insights shade light on tradeoffs between various parameters such as vehicle load, speed and total cost, and offers insight on economies of 'environmental-friendly' vehicle routing. This research paper's contributions include (i) Incorporation of fuel consumption and carbon-di-oxide emissions into existing planning methods for vehicle routing (ii) Development of a new integer programming formulation for the VRP. This novel mathematical model, in contrast to most of the existing models, minimizes a total cost function which includes emission constraint. This cost function is composed of labor, fuel and emission costs expressed as a function of load and speed.

Design of sustainable supply chains under the emission trading scheme is studied by Chaabane et al. (2010). This paper introduces a mixed-integer linear programming based framework for sustainable supply chain design. Their mathematical model considers life cycle assessment (LCA) principles in addition to the traditional material balance constraints at each node in the supply chain. It considers limit on carbon emission and determines the number of carbon credits to be bought and sold.

Green supply chain network design to reduce carbon emissions is discussed by authors Elhedhli and Merrick (2012). The relationship between carbon-di-oxide emissions and vehicle weight is modeled using a concave function leading to a concave minimization problem. Lagrangian relaxation is used to decompose the problem into a capacitated facility location problem with single sourcing. This makes it a concave knapsack problem that can be solved. Concave mixed integer programming model is tackled using Lagrangian relaxation.

Research paper written by Absi et al. (2013) explains lot sizing with carbon emission constraints. This research paper deals with finding the carbon emission per product produced. The authors consider periodic carbon emission constraint, rolling carbon emission constraint, cumulative carbon emission constraint, and global carbon emission constraint.

Green supply chain network optimization and the trade-off between environmental and economic objectives is studied by Tognetti et al. (2015). They establish interplay between

emissions, costs of the supply chain contingent upon the production volume allocation and the energy mix. The results, based on a case study in the German automotive industry, show that by optimizing the energy mix, the carbon-di-oxide emissions of the supply chain can be reduced by 30% at almost zero variable cost increase.

The single-item green lot-sizing problem with fixed carbon emissions has been discussed by Absi et al . (2015). The research paper efficiently explains how to calculate the amount of emission per product. The problem deals with determining which node to be selected in each period such that no carbon emission constraint is violated. Further, cost of satisfying all the demands on a given time horizon is also minimized. MILP model is formulated.

The economic lot-sizing problem with an emission capacity constraint is studied by Helmrich et al. (2015). Authors calculate the emission per unit production. They provide a Lagrangian heuristic to provide a feasible solution. For costs and emissions values such that the zero inventory property is satisfied, they give a pseudo-polynomial algorithm, which can also be used to identify the complete set of Pareto optimal solutions of the bi-objective lot-sizing problem. Furthermore, for such costs and emissions, they present a fully polynomial time approximation scheme (FPTAS). They extend it to deal with general costs and emissions. Special attention is paid to an efficient implementation. An improved rounding technique is used to reduce the posteriori gap. The same technique is also used for combination of the FPTAS and heuristic lower bound. Extensive computational tests show that the Lagrangian heuristic gives solutions that are very close to the optimum.

Authors Xiaoli and Li (2010) research on the optimization of carbon emissions from distribution centers and propose Genetic algorithm for solving large size problem. The concept behind this research area is that emission is associated even with inventory. This paper proposes a MILP model to decide optimum locations of distribution centers. This research paper aims to minimize the carbon emissions of entire logistics system. Euclidean distance is considered between facility and warehouse and demand points. However, they do not consider emission factor and total emission cap constraint.

2.3   Research Contribution

The primary objective of any SCND model has always been the identification of the network configuration with the least total cost. According to Correia et al. (2013) facility location and logistics costs (e.g., for production and distribution) are among the most frequent cost components.

The contribution of this thesis in comparison to the existing literature is as follows:

1. Modelling, formulation and design of the USA-Canada cross border supply chain network itself is a new emerging research area. FLAP have been studied before. However, its specific application to USA-Canada cross border supply chain considering disruption has never been done before. In this thesis we address FLAP specific to the USA-Canada cross border SCND.

2. Disruption scenario specific to customer demand and the probability of occurrence of corresponding disruption scenarios have not been considered previously in any mixed integer linear programming model.

3. In this thesis, a novel emission constraint has been introduced in supply chain network design to limit the amount of Carbon-di-oxide emission below permissible limits per manufacturer per year. Also, to the author's knowledge a simulated annealing based metaheuristic for FLAP problem considering emission control has not been studied before in the literature.

3   Methodology

3.1   Problem Description

Mathematical model developed in this thesis consists of set of locations (*V*) and customers (*U*) spread across the USA and Canada. Each location has a facility with default existing production capacity (H_k). This assigned capacity can be added / dismantled, from predefined set of capacities, based on changing customer demand over the planning horizon. Cost is incurred whenever a capacity is added / dismantled to an existing capacity. Customer demand can be satisfied by multiple facilities. In the developed model, customer demand parameter is deterministic and changes with time. For each time period demand is fixed and supply should be greater than or equal to demand.

Scenario can be described as a specific event or instance. For example: consider a disruption scenario let's say "Orange alert at Ambassador Bridge". Assume that this scenario occurs. To incorporate this scenario in our model we consider the probability of occurrence of this scenario (Ps). The user can set probability of scenario as per measures. Model is developed in such a way that a single time period contains multiple scenarios.

Customer demand is discrete but deterministic and changes with respect to time. Time period can be described as duration for each demand. A time period can be a single day, a week, a month, a year. Our model is robust and the user may take the time period as per his requirements. Hence, based on the user requirements, demand could be taken as annual demand, weekly demand and daily demand. Sum of all time period makes the planning horizon. $h_{i,t}$ Parameter is used to incorporate the customer demand for each time period into our model.

Every facility can supply every customer, irrespective of its location (USA or Canada). When a facility transports goods within the country, it uses domestic routes and incurs only domestic cost of transportation. On the other hand when a facility transports goods to its customers across border, it has to ship via cross border routes. In such scenario there is an extra cost incurred (e_s) due to disruption at cross border. As per the law, every manufacturing facility should maintain CO_2 emission below permissible limits. Hence, we include emission constraint to restrict total production done by each facility per year in order to achieve emission target specified by law.

Objective of the thesis is to minimize cost of entire supply chain by finding optimum quantity of goods to be produced and shipped ($z_{j,i,s,t}$). Also, it aims to find instances at which there is a need to construct/dismantle a capacity at any given facility.

Following map give a pictorial representation of cross border supply chain

Figure 2 Cross Border Supply Chain USA –Canada

3.2   Assumptions

Following assumption are made while developing ILP model:

1.   At any facility, only one capacity can be constructed/dismantled at any given time period.

2.   Number of existing customers and facilities are known.

3.   A facility is considered as a supplier. Supplier directly supplies to customer.

4.   Facility locations are fixed and do not change over the planning horizon. Each facility has to have an initial default existing capacity.

5.   A single facility can supply to multiple customers.

6.   We assume that inventory is either 0 or fixed at the end of time period. Inventory parameter being constant is hence excluded. All goods produced are shipped to the customers. Neither facility nor do customers have inventory.

7.   Annual customer demand is considered to be deterministic and changes over the period of time

8.   Border crossing disruptions in supply chain are associated with scenario.

9.   It is assumed that each facility uses green technology for manufacturing goods.

10.   Only one capacity can be constructed from the available set of capacities at any time period for any particular facility.

11.   Only one capacity can be dismantled from the available set of capacities at any time period for any particular facility

12.   Orders for parts are placed at the start of the planning horizon, when all customer orders for products are known

13.   All parts ordered from a supplier are shipped together in a single delivery

14.   Customer orders are satisfied at the end of each time period and no backlog exists.

3.3 Parameters

U= set of all customers ($U1 \cup U2$)

$U1$= set of customers in USA

$U2$ = set of customers in Canada

V = set of all locations ($V1 \cup V2$)

$V1$= set of possible locations of facilities in USA

$V2$= set of possible locations of facilities in Canada

S= set of all scenarios

$d_{j,i,t}$ = Present value of production and transportation cost of one unit per year from location j to customer i at time t

p_s = Probability of scenario s

$E1$ = set of domestic routes $\left\{ (j,i) : j \in V1, i \in U1 \ or \ j \in V2, i \in U2 \right\}$

$E2$= set of cross border routes $\left\{ (j,i) : j \in V1, i \in U2 \ or \ j \in V2, i \in U1 \right\}$

e_s = Increase in cost of crossing border in scenario s

$h_{i,t}$= Demand at customer i in units per time period t

$\widehat{H}_j$= The existing capacity in units per time period in location $j \in V$

H_k= The kth capacity in units per year, $|V| \times H_{max} \geq \sum_{i \in U} h_i$

$a_{j,k,t}$ = Fixed cost of setting up a facility of capacity H_k in location j at time t

$\overline{a}_{j,k,t}$ = Fixed cost of removing a capacity H_k at location j at time t

α= Cost of each carbon credit

$e_{j,i}=$ emission factor due to production and transportation per unit from facility j to customer $i = 1$

$E =$ Carbon credits allocated to each manufacturer at beginning of planning horizon = 200 thousand tons.

$\Omega =$ maximum emission capacity per facility per time period set by government = 25000 tons of CO_2

3.4 Indices

i: Customers, $i \in U$

j: Locations, $j \in V$

s: Scenarios, $s \in S$

k: Capacities , $k \in K$

t: Time period , $t \in T$

3.5 Decision Variables

We define binary variables,

$Z_{j,i,s,t} =$ Quantity of demand transported from facility j to customer i in scenario s in period t $\forall\ i \in U,\ j \in V, s \in S, t \in T$

$y_{j,k,t} = \begin{cases} 1 & \text{Capacity k is set up at} \\ & \text{location j, at time t,} \forall\ j \in V, k \in K, t \in T \\ \\ 0 & \text{Otherwise} \end{cases}$

$$\hat{y}_{j,k,t}= \begin{cases} 1 & \text{Capacity k is dismantled at} \\ & \text{location j at time t} \ \forall \ \ j \in V, t \in T, k \in K \\ \\ 0 & \text{Otherwise} \end{cases}$$

3.6   Objective Function

Minimize

$$\sum_{t \in T}\{\sum_{j \in V}\sum_{k \in K} a_{j,k,t}\, y_{j,k,t} \ + \ \sum_{k \in K}\sum_{j \in V} \bar{a}_{j,k,t}\, \hat{y}_{j,k,t} + \ \sum_{(j,i)\in E1}\sum_{s \in S} d_{j,i,t}\, Z_{j,i,s,t,} \ +$$

$$\sum_{(j,i)\in E2}\sum_{s \in S} d_{j,i,t}\, Z_{j,i,s,t,}(1+e_s)\}+ \sum_{i \in U}\sum_{s \in S}\sum_{j \in V}\sum_{t \in T} Z_{j,i,s,t} \times e_{j,i} \times \alpha \ - E \times \alpha$$

3.7   Constraints

$$\sum_{j \in V} Z_{j,i,s,t} \geq h_{i,t} \times p_s \qquad \forall\, i \in U, t \in T\,, s \in S \tag{1}$$

$$\sum_{i \in U}\sum_{s \in S} Z_{j,i,s,t} \ \leq \hat{H}_j + \sum_{t' \leq t}\sum_{k \in K} y_{j,k,t'}\, H_k - \sum_{t' \leq t}\sum_{k \in K} \hat{y}_{j,k,t}\, H_k \quad \forall j \in V, t \in T \tag{2}$$

$$\sum_{i \in U}\sum_{s \in S} Z_{j,i,s,t} \times e_{j,i} \leq \Omega \qquad \forall\, j \in V, t \in T \tag{3}$$

$$\sum_{k \in K} \hat{y}_{j,k,t} \leq 1 \qquad \forall\, j \in V, t \in T \tag{4}$$

$$\sum_{k \in K} y_{j,k,t} \leq 1 \qquad \forall\, j \in V, t \in T \tag{5}$$

$$\sum_{t'=1}^{t-1}\sum_{k \in K} y_{j,k,t'} \times H_k + \hat{H}_j \geq \ \sum_{t'=1}^{t}\sum_{k \in K} \hat{y}_{j,k,t'} \ \times H_k \qquad \forall j \in V, t \geq 2 \tag{6}$$

$$\sum_{k \in K} \hat{y}_{j,k,t=1} \times H_k \leq \hat{H}_j \qquad \forall j \in V \tag{7}$$

$$Z_{j,i,s,t} \geq 0 \qquad \forall\, i \in U, j \in V, s \in S\,, t \in T \tag{8}$$

$$y_{j,k,t} \in \{0,1\} \qquad \forall\, j \in V, t \in T, k \in K \tag{9}$$

$$\hat{y}_{j,k,t} \in \{0,1\} \qquad \forall\, j \in V, t \in T, k \in K \tag{10}$$

3.8   Explanation

Objective function:

The objective function has six terms:

- The first term of the objective function calculates the total cost of setting up capacities at respective facilities over the planning horizon.
- The second term of the objective function calculates the total cost of dismantling capacities at respective facilities over the planning horizon.
- The third term of objective function calculates the domestic cost of transporting goods within the USA or Canada.
- The forth term calculates the cost of the cross–border transportation. This includes the extra cost incurred in transporting goods from the USA-Canada border.
- The fifth term of the objective function calculates the total amount of carbon emission by all the facilities in terms of carbon di oxide credits. Multiplying these total number of carbon credits with cost of each carbon credit gives total cost incurred due to carbon di oxide emission.
- The sixth term of the objective function specifies the total carbon credits allocated to each facility at the beginning of planning horizon. Also, it calculates the cost associated with those initial carbon credits. However, since it is a constant we exclude the term from our objective function henceforth.

Constraint 1: Mentions that the total expected demand of each customer across each scenario for each time period is satisfied. Customer's annual demand is known. This demand is multiplied by the probability of occurrence of the scenario which gives us the expected demand at that particular scenario.

Constraint 2: Ensures that production is always greater than the goods supplied. For every facility across each time period the total production has to be always greater than the total goods supplied by the facility to all its customers.

Constraint 3: Specifies that the total emission for each facility is within limit specified by the government law. The allowable emission is calculated based on the total production done by the

facility each year times the emission factor when green technology is used for production. Emission factor is predefined as per the Kyoto protocol.

Constraint 4: For any facility at any time period only one capacity can be dismantled

Constraint 5: For any facility at any time period only one capacity can be constructed

Constraint 6: Developed model allows constructing and dismantling of the facilities over the planning horizon. Hence, this constraint is designed to ensure that for each facility, the total sum of capacities constructed, including the existing capacity of the facility, over the planning horizon is always greater than the total sum of the capacities dismantled for that facility, over the planning horizon.

Constraint 7: In the developed model since the capacities can be dismantled, there is a need to ensure that every facility has a default existing capacity. If the sum of dismantled capacities in the first time period is more than the existing default capacity for that facility then the above mentioned condition is violated.

Constraint 8: Restricts integer values for decision variable $Z_{j,i,s,t}$

Constraint 9 and 10: Ensures binary values for decision variables $y_{j,k,t}$ and $\hat{y}_{j,k,t}$

4   Policy Analysis

In this section we have explained some of the potential real life applications of the developed mathematical model. Also, this section illustrates some of the basic concepts used in designing the model. These managerial insights illustrate how developed model helps supply chain managers in effective decision making process.

Customer demand for every scenario is satisfied completely. The mathematical model is designed in such a way that there can be multiple scenarios is single time period. Mathematical model will allow managers to ensure which is the best possible scenario to ship goods so that their customer demand is met for each time period.

4.1   Meeting Demand for Each Scenario

For instance, assume

The duration of each scenario: one day;

Time Period: one year;

N: Number of days in each year;

Total number of scenarios: $s1 + s2 = S$

$Z_{j,i,s,t}$ = Quantity of demand transported from facility j to customer i in scenario s in period t

p_s = Probability of scenario s

$N \times p_s$ = Expected number of days per year for scenario s

$Z_{j,i,s,t}$ = Annual supply in $N \times p_s$ days

$$\frac{\sum_{j \in V} Z_{j,i,s,t}}{N * p_s} = \text{Daily supply from all facilities to customer } i \text{ in scenario } s \qquad (11)$$

$$\frac{h_{i,t}}{N} = \text{Daily customer demand in time period } t \qquad (12)$$

As, Supply $\geq$ demand

$$\frac{\sum_{j \in V} Z_{j,i,s,t}}{N * p_s} \geq \frac{h_{i,t}}{N} \tag{13}$$

Hence, to ensure that demand is satisfied in each scenario demand constraint is incorporated:

$$\sum_{j \in V} Z_{j,i,s,t} \geq h_{i,t} \times p_s \qquad \forall i \in U, t \in T, s \in S$$

(14)

For example: if we consider a disruption scenario, let's say "heavy snowfall on the bridge while the shipment crosses USA-Canada Border". Assume that this disruption scenario occurs. To incorporate this in our model we consider the probability of occurrence associated with this scenario (p_s).

If the above scenario occurs, then the supply in that scenario is disrupted. This disruption incurs additional costs while crossing the border which is why we include the parameter e_s associated with it. Hence, to optimize the cost and fulfill customer demand by the end of each time period the developed model gives results showing in which scenario what quantity of goods has to be transported.

4.2   Facility Location Allocation Problem

In developed mathematical model there exists a set of domestic and international routes for corresponding shipments. As mentioned, the problem belongs to Facility Location Allocation Problem and not for Facility Routing Problem. Hence, the developed model does not consider a separate route in each scenario.

Use of developed model to cope up with uncertainty and risks involved in supply chain:

Supply chain management systems are increasingly growing complex. Tremendous uncertainty is involved at every step of the chain network. This uncertainty leads to risk at every stage and hence managers need to make decisions under uncertain conditions. Therefore, finding risk involved, analyzing it and then developing mitigating plan is important. All departments related to supply chain such as finance, insurance, operations are integrated and hence importance of considering risk is understood by all. Wrong decisions taken due to risk causes adverse economic impact or a decrease in the performance of the business. Risk can also be defined as anything that disrupts the information, raw material or product flows delivered from original supplier to ultimate end- user. Supply chain risk and uncertainty is difficult to assess,

monitor, control and difficult to incorporate in the math model. Monetary losses due to risks are loss of profit, in-efficiency due to over spending, less net present worth of the invested amount, loss of customer good will and satisfaction, wrong supplier selection.

Our developed model solves for optimal quantity to be produced and supplied by each supplier to its customers and hence reduces the risk involved in the supply chain. With the use of developed model, managers will be in better position to take decisions under uncertainty.

Use of developed model to reduce the bullwhip effect:

The bullwhip effect is phenomenon where order variability goes on increasing as the orders move upstream (from end-user customer to manufacturer) in the supply-chain. Price variability results in demand variability. This effect becomes significant when the cost from fluctuations in production/ordering exceeds the cost of holding inventory. Costs incurred due to bullwhip effect are:

1. Setting up and shutting down machines: In case of bullwhip effect capacitated supply chain is the only agile and dynamic design that allows construction/dismantling of installed machines. Developed model exactly tells when the capacities need to be changed.

2. Idling and overtime in the workload or Hiring and firing of the workforce: Developed model takes into account the aggregate capacity management option in which optimized results tend to minimize the worker and machine idle time according to the customer demand. Else it goes for other capacity management options like part time temporary workers or adjusting existing workers.

3. Excessive inventory at the manufacturer: In order to maintain an un-interrupted supply the customers till the disruption lasts excess inventory is maintained at the manufacturers end. This way a high service level can be achieved but with a high cost.

4. Difficulty in forecasting and scheduling: Forecasting is capable of achieving the highest possible accuracy in a supply chain. Due to bullwhip effect it becomes difficult to forecast which ultimately leads to incorrect ordering.

5. Learning and training new recruits: As due to bullwhip effect, at times, it is necessary to recruit/fire labors. Whenever new recruits join they need to be trained. Hence, substantial amount of time and money is to be invested in this process.

Many of the other consequences of the bull-whip effect cannot be quantified economically. The developed model returns the exact values to be produced even in case of abrupt change in customer demand thus minimizing the bullwhip effect.

Use of developed model for Supplier selection:

In customer-driven supply chains also called as pull system, customer orders are full-filled immediately after arrival of raw material. The ordered products are delivered to customers by the suppliers/manufacturer immediately on completion.
Following are some of the options available for supplier selection:

1. Global sourcing from low cost countries

2. Implementing lean operations and manufacturing processes at supplier/ manufacturer end.

3. Use of green technologies for manufacturing

4. Desired service level from the supplier along with maintaining high quality.

Use of developed model for integrated supply, production and distribution scheduling under disruption risks:

Aim of supply chain manager is to effectively prepare a production plan and delivery schedule even under disruption risks. Developed model allows both. Following are few other options which the managers can opt for based on the results obtained from developed model.

1. Maintaining high volume of production and inventory so that stock lasts till disruption is recovered and uninterrupted supply is maintained to the customer.

2. Designing agile supply chain

4.3   Border Costs

The presence of USA-Canada border increases the cost of cross border shipment due to disruptions

The mathematical model is designed keeping the border crossing costs into consideration. The disruption scenario in which a shipment crosses the border, corresponding additional costs associated with it are included in objective function. This parameter is e_s=Increase in cost of crossing border in scenario s

In case of absence of bridge these costs would not be present and e_s would be zero for its corresponding scenario. The value of the objective function changes in case if the bridge is not present. A case study is discussed below, to prove that presence of border increases the overall costs of supply chain.

Test Case: No Bridge for cross border shipment

ABC Print Inc. is a manufacturer of printing material used in to make business cards. It requires raw material in the form of rubber. Currently, ABC Print Inc. has 4 manufacturing centers located in Windsor, Detroit, Waterloo, and Toronto. ABC Print Inc. receives raw material from its supplier which are located across USA and Canada in New York, Chicago, Hamilton and Ottawa. The supplier has to select best strategy to minimize the capacity management cost while satisfying demand. Additional constraint is that if the shipment crosses the border and if there is disruption at that particular scenario, then there is a 90 % extra cost incurred due to disruption. Each time period has two scenarios; Day and Night. As per Kyoto Protocol, each supplier has to limit its production such that the total emission caused is less than permissible value by law.

Requirement is to develop Integer Linear Programming Model which would:

1.   Allow ABC Print Inc. to allocate suppliers to its facilities i.e. decide which supplier should ship what quantity to respective facilities.

2.   Allow each supplier to know the optimized production schedule i.e. decision regarding what quantity to be produced and shipped in which time period

3.   To use aggregate capacity management and determine appropriate economic strategy *i.e* allow suppliers to know in advance how much capacity they will need to satisfy the customer demand in corresponding time period.

4.   Allow ABC Print Inc. to know total cost of their supply chain.

ABC Print Inc. wants to know how much cost they would save if they avoid using bridge for cross border shipment

Following data values for concerned parameters have been in used in math model:

Ps: [0.5, 0.5]

es: [0, 0]

cap: [50, 60, 70]

$\widehat{H}_j$: [50, 60, 70, 70]

$h_{i,t}$: [10, 20, 30, 40, 50, 60, 70, 80]

$a_{j,k,t}$: [10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60, 10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60]

$\overline{a}_{j,k,t}$: [10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60, 10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60]

$d_{j,i,t}$:[1 ,2 ,3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1 2, 3, 4, 5, 6, 7, 8, 9, 10 11, 12, 1, 2, 3, 4 ,5, 6, 31, 32]

Following results are obtained in which demand is satisfied for each customer in each scenario without violating capacity constraint for each facility.

Decision variable $y_{j,k,t}$ remain unchanged:

Table 2 y_(j,k,t) values_no border

T	capacities	V	$y_{j,k,t}$
1	1	1	1
1	3	3	1
2	1	1	1
2	3	3	1

Table 3 $Z_{t,sj,i}$ values_time1_no border

			Customer (i)			
	Time Period	Scenario	Windsor	London	Detroit	Toronto
			1	2	3	4
	$t = 1$	S	$Z_{t,sj,i}$			
	1 New York	1	z(1,1,1,1)=5	z(1,1,1,2)=10	z(1,1,1,3)=15	z(1,1,1,4)=0
		2	z(1,2,1,1)=5	z(1,2,1,2)=10	z(1,2,1,3)=15	z(1,2,1,4)=20
	2 Chicago	1	z(1,1,2,1)=0	z(1,1,2,2)=0	z(1,1,2,3)=0	z(1,1,2,4)=0
		2	z(1,2,2,1)=0	z(1,2,2,2)=0	z(1,2,2,3)=0	z(1,2,2,4)=0
Facility (j)	3 Hamilton	1	z(1,1,3,1)=0	z(1,1,3,2)=0	z(1,1,3,3)=0	z(1,1,3,4)=0
		2	z(1,2,3,1)=0	z(1,2,3,2)=0	z(1,2,3,3)=0	z(1,2,3,4)=0
	4 Ottawa	1	z(1,1,4,1)=0	z(1,1,4,2)=0	z(1,1,4,3)=0	z(1,1,4,4)=20
		2	z(1,2,4,1)=0	z(1,2,4,2)=0	z(1,2,4,3)=0	z(1,2,4,4)=0
		Demand	10	20	30	40

Table 4: $Z_{t,sj,i}$ values_time2_no border

			Customer (i)			
	Time Period	Scenario	Windsor	London	Detroit	Toronto
			1	2	3	4
	$t = 2$	S	$Z_{t,sj,i}$			
	1 New York	1	z(2,1,1,1)=25	z(2,1,1,2)=30	z(2,1,1,3)=30	z(2,1,1,4)=0
		2	z(2,2,1,1)=0	z(2,2,1,2)=0	z(2,2,1,3)=0	z(2,2,1,4)=0
	2 Chicago	1	z(2,1,2,1)=0	z(2,1,2,2)=0	z(2,1,2,3)=0	z(2,1,2,4)=0
		2	z(2,2,2,1)=0	z(2,2,2,2)=0	z(2,2,2,3)=0	z(2,2,2,4)=0
Facility (j)	3 Hamilton	1	z(2,1,3,1)=0	z(2,1,3,2)=0	z(2,1,3,3)=5	z(2,1,3,4)=40
		2	z(2,2,31,)=0	z(2,2,3,2)=0	z(2,2,3,3)=35	z(2,2,3,4)=40
	4 Ottawa	1	z(2,1,4,1)=25	z(2,1,4,2)=0	z(2,1,4,3)=0	z(2,1,4,4)=0
		2	z(2,2,4,1)=0	z(2,2,4,2)=30	z(2,2,4,3)=0	z(2,2,4,4)=0
		Demand	50	60	70	80

Result Analysis: If there is no bridge, there would be no disruption scenarios associated with the bridge. Hence, there would be no extra cost incurred in crossing the bridge. In this particular case, the parameter e_s for all scenarios would be zero. Due to this reason the cost of supply chain has decreased for the same parameters as aggregate planning test case.

❖ **Total cost of supply chain = objective function value = 7000 $**

4.4 Aggregate Planning

Managers can make use of aggregate planning for capacity management to select economic production strategy.

In developed model, long term capacity management as well as short term capacity management options are considered. If the demand grows with time more capacities are added up for a particular facility. Similarly, if the demand decreases with time, capacities are dismantled. These capacities are added/dismantled from a set of predefined capacities.

For any plant, if the demand exceeds its production capacity then some of the short term capacity management methods to incorporate additional capacities includes:

1. Overtime

2. Additional shifts

3. Sub-Contracting / Outsourcing

4. Part time workers

If the demand is still not satisfied, long term capacity management options are used which include:

1.   Construction of an additional manufacturing plant to increase the production capacity.

For example: If the company has less production capacity than demand for a particular time period, then optimal solution obtained from this model will allow managers to determine whether they have to go for short term capacity management or they should invest in long term. Developed math model optimization results help managers to decide which strategy to go for. For instance, the below table shows relation between capacity management option to be used at corresponding capacity values (k) obtained from decision variable $y_{j,k,t}$

Table 5: Aggregate Planning

$y_{j,k,t}$	Capacity Value= (k)	Capacity Management option to be used	Cost of adding capacity($a_{j,k,t}$)	Cost of removing capacity($a_{j,k,t}$)
$y_{j,1,t}$	50	Use Overtime for 1 shift	100 $	200 $
$y_{j,2,t}$	60	Use of part time workers	300 $	400 $
$y_{j,3,t}$	70	Construction of a new plant	600 $	1200 $

4.5   Aggregate Planning Test Case

ABC Print Inc. is a manufacturer of printing material used in to make business cards. It requires raw material in the form of rubber. Currently, ABC Print Inc. has 4 manufacturing centers located in Windsor, Detroit, Waterloo, and Toronto. ABC Print Inc. receives raw material from its supplier which are located in across USA and Canada in New York, Chicago, Hamilton and Ottawa. The supplier has to select best strategy to minimize the capacity management cost while satisfying demand. Additional constraint is that if the shipment crosses the border and if there is disruption at that particular scenario, then there is a 90 % extra cost incurred due to disruption. Each time period has two scenarios; Day and Night. Last constraint, as per Kyoto Protocol, each supplier has to limit its production such that the total emission caused is less than permissible value by law.

Requirement is to develop Integer Linear Programming Model which would:

1.   Allow ABC Print Inc. to allocate suppliers to its facilities i.e. decide which supplier should ship what quantity to respective facilities.

2.   Allow each supplier to know the optimized production schedule i.e. decision regarding what quantity to be produced and shipped in which time period

3.   **To use aggregate capacity management and determine appropriate economic strategy *i.e* allow suppliers to know in advance how much capacity they will need to satisfy the customer demand in corresponding time period.**

4.   Allow ABC Print Inc. to know total cost of their supply chain.

Each of the suppliers have a default existing production capacity. Following table gives the default existing capacities of each supplier:

Table 6: Supplier Default Capacities

Supplier location	Capacity(Metric Ton)
New York	50
Chicago	60
Hamilton	70
Ottawa	70

ABC Print Inc. places its order for every 2 days. Demand at each manufacturing locations of ABC Print Inc. is as follows:

Table 7: Customer Demand

Location	Demand(Metric Tons)	
Windsor	10(Day 1)	50(Day 2)
Detroit	20(Day 1)	60(Day 2)
London	30(Day 1)	70(Day 2)
Toronto	40(Day 1)	80(Day 2)

ABC Print Inc. requires high service level and uninterrupted supply. To achieve the same each supplier has to use aggregate planning for capacity management and finding economic strategy to satisfy demand. Following are the mixed strategy option to increase or decrease capacity as per demand along with the associated cost.

Table 8: Aggregate Planning

$y_{j,k,t}$	Capacity (Mt)	Capacity Management option to be used	Cost of adding capacity($a_{j,k,t}$)	Cost of removing capacity($a_{j,k,t}$)
$y_{j,1,t}$	50	Use Overtime for 1 shift	100 $	200 $
$y_{j,2,t}$	60	Use of part time workers	300 $	400 $
$y_{j,3,t}$	70	Construction of a new plant	600 $	1200 $

Figure 3 Cross Border Supply Chain

ILP model was programmed using Mosel language and solved using Xpress Optimizer 7.6, 64 bit. Following results were obtained after running the model.

Ps: [0.5, 0.5]

es: [0.9, 0.9]

cap: [50, 60, 70]

$\widehat{H}_j$: [50, 60, 70, 70]

$h_{i,t}$: [10, 20, 30, 40, 50, 60, 70, 80]

$a_{j,k,t}$: [10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60, 10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60]

$\overline{a}_{j,k,t}$: [10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60, 10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60]

$d_{j,i,t}$:[1 ,2 ,3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1 2, 3, 4, 5, 6, 7, 8, 9, 10 11, 12, 1, 2, 3, 4 ,5, 6, 31, 32]

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Decision variable $y_{j,k,t}$:

Table 9: $y_{j,k,t}$ decision variable

T	capacities	V	$y_{j,k,t}$
1	1	1	1
1	3	3	1
2	1	1	1
2	3	3	1

Decision variable $Z_{t,sj,i}$ values:

Table 10: $Z_{t,sj,i}$ decision variable time period 1

			Customer (i)			
	Time Period	**Scenario (Disruption)**	Windsor	London	Detroit	Toronto
			1	2	3	4
	$t = 1$	$S = 2$		$Z_{t,sj,i}$		
1	New York	1	z(1,1,1,1)=5	z(1,1,1,2)=10	z(1,1,1,3)=0	z(1,1,1,4)=0
		2	z(,12,1,1)=5	z(1,2,1,2)=10	z(1,2,1,3)=0	z(1,2,1,4)=0
2	Chicago	1	z(1,1,2,1)=0	z(1,1,2,2)=0	z(1,1,2,3)=0	z(1,1,2,4)=0
		2	z(1,2,2,1)=0	z(1,2,2,2)=0	z(1,2,2,3)=0	z(1,2,2,4)=0
Facility (j) 3	Hamilton	1	z(1,1,3,1)=0	z(1,1,3,2)=0	z(1,1,3,3)=0	z(1,1,3,4)=0
		2	z(1,2,3,1)=0	z(1,2,3,2)=0	z(1,2,3,3)=0	z(1,2,3,4)=0
4	Ottawa	1	z(1,1,4,1)=0	z(1,1,4,2)=0	z(1,1,4,3)=15	z(1,1,4,4)=20
		2	z(1,2,4,1)=0	z(1,2,4,2)=0	z(1,2,4,3)=15	z(1,2,4,4)=20
		Demand	10	20	30	40

Table 11: $Z_{t,sj,i}$ decision variable time period 2

			Customer (i)			
	Time Period	**Scenario (Disruption)**	Windsor	London	Detroit	Toronto
			1	2	3	4
	$t = 2$	$S = 2$		$Z_{t,sj,i}$		
1	New York	1	z(2,1,1,1)=25	z(2,1,1,2)=10	z(2,1,1,3)=0	z(2,1,1,4)=0
		2	z(2,2,1,1)=25	z(2,2,1,2)=30	z(2,2,1,3)=10	z(2,2,1,4)=0
2	Chicago	1	z(2,1,2,1)=0	z(2,1,2,2)=20	z(2,1,2,3)=0	z(2,1,2,4)=0
		2	z(2,2,2,1)=0	z(2,2,2,2)=0	z(2,2,2,3)=0	z(2,2,2,4)=0
Facility (j) 3	Hamilton	1	z(2,1,3,1)=0	z(2,1,3,2)=0	z(2,1,3,3)=35	z(2,1,3,4)=40
		2	z(2,2,3,1)=0	z(2,2,3,2)=0	z(2,2,3,3)=25	z(2,2,3,4)=40
4	Ottawa	1	z(2,1,4,1)=0	z(2,1,4,2)=0	z(2,1,4,3)=0	z(2,1,4,4)=0
		2	z(2,2,4,1)=0	z(2,2,4,2)=0	z(2,2,4,3)=0	z(2,2,4,4)=0
		Demand	50	60	70	80

Result analysis: On getting optimized results from the developed math model and reading the parameter $y_{j,k,t}$ it can be inferred that in first time period one facility at New York makes use of capacity management option "Overtime for 1 shift" in order to satisfy the demand. While in the same time period, facility at Hamilton makes use of long term capacity management option like "construction of a new plant"

❖ Total cost of supply chain = objective function value = 7163 $

4.6   Excess Disruption Scenarios

When the amount of disruption increases on the border crossing, supply chain managers should be able to decide in which scenario the shipments have to be done. Developed model gives us the results to which scenario shipment has to be done such that the optimal cost of supply chain would be obtained.

ABC Print Inc. is a manufacturer of printing material used in to make business cards. It requires raw material in the form of rubber. Currently, ABC Print Inc. has 4 manufacturing centers located in Windsor, Detroit, Waterloo, and Toronto. ABC Print Inc. receives raw material from its supplier which are located in across USA and Canada in New York, Chicago, Hamilton and Ottawa. The supplier has to select best strategy to minimize the capacity management cost while satisfying demand. Additional constraint is that if the shipment crosses the border and if there is disruption at that particular scenario, then there is a 90 % extra cost incurred due to disruption. Each time period has four scenarios; Morning, afternoon, evening, night. Last constraint, as per Kyoto Protocol, each supplier has to limit its production such that the total emission caused is less than permissible value by law.

Requirement is to develop Integer Linear Programming Model which would:

1.   Allow ABC Print Inc. to allocate suppliers to its facilities i.e. decide which supplier should ship what quantity to respective facilities.

2.   Allow each supplier to know the optimized production schedule i.e. decision regarding what quantity to be produced and shipped in which time period

3.   To use aggregate capacity management and determine appropriate economic strategy *i.e* allow suppliers to know in advance how much capacity they will need to satisfy the customer demand and its corresponding time period.

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4.   Allow ABC Print Inc. to know which total cost of their supply chain.

With more number of disruption scenarios involved in shipping, the cost of supply chain increases as more disruption leads to more cost. The number of scenarios are total 4 and disruption is present in all scenarios.

Data file used in this case is:

P_s: [0.25, 0.25, 0.25, 0.25]

es: [0.9, 0.9, 0.9, 0.9]

cap: [50, 60, 70]

$\widehat{H}_j$: [50, 60, 70, 70]

$h_{i,t}$: [10, 20, 30, 40, 50, 60, 70, 80]

$a_{j,k,t}$: [10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60, 10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60]

$\overline{a}_{j,k,t}$: [10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60, 10, 10, 10, 10, 30, 30, 30, 30, 60, 60, 60, 60]

$d_{j,i,t}$:[1 ,2 ,3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1 2, 3, 4, 5, 6, 7, 8, 9, 10 11, 12, 1, 2, 3, 4 ,5, 6, 31, 32]

Table 12: $Z_{j,i,s,t}$ *values_time1_scenario case*

Time Period			Scenario	Customer (i)			
				Windsor	London	Detroit	Toronto
			Disruption	1	2	3	4
$t = 1$			$S = 4$	$Z_{t,s,j,i}$			
Facility (j)	1	New York	1	z(1,1,1,1)=3	z(1,1,1,2)=5	z(1,1,1,3)=0	z(1,1,1,4)=0
			2	z(1,2,1,1)=3	z(1,2,1,2)=5	z(1,2,1,3)=0	z(1,2,1,4)=0
			3	z(1,3,1,1)=3	z(1,3,1,2)=5	z(1,3,1,3)=0	z(1,3,1,4)=0
			4	z(1,4,1,1)=1	z(1,4,1,2)=5	z(1,4,1,3)=0	z(1,4,1,4)=0
	2	Chicago	1	z(1,1,2,1)=0	z(1,1,2,2)=0	z(1,1,2,3)=0	z(1,1,2,4)=0
			2	z(1,2,2,1)=0	z(1,2,2,2)=0	z(1,2,2,3)=0	z(1,2,2,4)=0
			3	z(1,3,2,1)=0	z(1,3,2,2)=0	z(1,3,2,3)=0	z(1,3,2,4)=0
			4	z(1,4,2,1)=0	z(1,4,2,2)=0	z(1,4,2,3)=0	z(1,4,2,4)=0
	3	Hamilton	1	z(1,1,3,1)=0	z(1,1,3,2)=0	z(1,1,3,3)=0	z(1,1,3,4)=0
			2	z(1,2,3,1)=0	z(1,2,3,2)=0	z(1,2,3,3)=0	z(1,2,3,4)=0
			3	z(1,3,3,1)=0	z(1,3,3,2)=0	z(1,3,3,3)=0	z(1,3,3,4)=0
			4	z(1,4,3,1)=0	z(1,4,3,2)=0	z(1,4,3,3)=0	z(1,4,3,4)=0
	4	Ottawa	1	z(1,1,4,1)=0	z(1,1,4,2)=0	z(1,1,4,3)=6	z(1,1,4,4)=10
			2	z(1,2,4,1)=0	z(1,2,4,2)=0	z(1,2,4,3)=8	z(1,2,4,4)=10
			3	z(1,3,4,1)=0	z(1,3,4,2)=0	z(1,3,4,3)=8	z(1,3,4,4)=10
			4	z(1,4,4,1)=0	z(1,4,4,2)=0	z(1,4,4,3)=8	z(1,4,4,4)=10
			Demand	10	20	30	40

	Time Period	Scenario (Disruption)	Customer (i)			
			Windsor	London	Detroit	Toronto
			1	2	3	4
	$t = 2$	$S = 4$		$Z_{t,s,j,i}$		
		1	z(2,1,1,1)=13	z(2,1,1,2)=15	z(2,1,1,3)=0	z(2,1,1,4)=0
	1 New York	2	z(2,2,1,1)=13	z(2,2,1,2)=15	z(2,2,1,3)=0	z(2,2,1,4)=0
		3	z(2,3,1,1)=10	z(2,3,1,2)=15	z(2,3,1,3)=0	z(2,3,1,4)=0
		4	z(2,4,1,1)=0	z(2,4,1,2)=15	z(2,4,1,3)=12	z(2,4,1,4)=0
		1	z(2,1,2,1)=0	z(2,1,2,2)=0	z(2,1,2,3)=0	z(2,1,2,4)=0
	2 Chicago	2	z(2,2,2,1)=0	z(2,2,2,2)=0	z(2,2,2,3)=0	z(2,2,2,4)=0
Facility (j)		3	z(2,3,2,1)=1	z(2,3,2,2)=0	z(2,3,2,4)=0	z(2,3,2,4)=0
		4	z(2,4,2,1)=13	z(2,4,2,2)=0	z(2,4,2,4)=0	z(2,4,2,4)=0
		1	z(2,1,3,1)=0	z(2,1,3,2)=0	z(2,1,3,3)=18	z(2,1,3,4)=20
	3 Hamilton	2	z(2,2,3,1)=0	z(2,2,3,2)=0	z(2,2,3,3)=18	z(2,2,3,4)=20
		3	z(2,3,3,1)=0	z(2,3,3,2)=0	z(2,3,3,3)=18	z(2,3,3,4)=20
		4	z(2,4,3,1)=0	z(2,4,3,2)=0	z(2,4,3,3)=4	z(2,4,3,4)=20
		1	z(2,1,4,1)=0	z(2,1,4,2)=0	z(2,1,4,3)=0	z(2,1,4,4)=0
	4 Ottawa	2	z(2,2,4,1)=0	z(2,2,4,2)=0	z(2,2,4,3)=0	z(2,2,4,4)=0
		3	z(2,3,4,1)=0	z(2,3,4,2)=0	z(2,3,4,3)=0	z(2,3,4,4)=0
		4	z(2,4,4,1)=0	z(2,4,4,2)=0	z(2,4,4,3)=0	z(2,4,4,4)=0
		Demand	50	60	70	80

Result Analysis: Based on the results obtained from the developed math model it can be inferred that as the number of disruption scenarios increases the cost of supply chain increases. As e_s takes 0.9 value for each scenario total supply chain cost increases compared to the situation in which there is no disruption. Had there been no disruption for all 4 scenarios then corresponding e_s value would be zero for each scenario.

❖ Total cost of supply chain = objective function value = 7349 $

4.7   Rate of Change of Demand

The developed model is flexible is enough to incorporate the abrupt changes in the customer demand. In case of emergencies managers need to have contingency plans ready to adjust to the dynamic customer demand. Our developed model can handle these abrupt changes in customer demands. Following example proves the sufficiency of the above stated point.

ABC Print Inc. is a manufacturer of printing material used in to make business cards. It requires raw material in the form of rubber. Currently, ABC Print Inc. has 4 manufacturing centers located in Windsor, Detroit, Waterloo, and Toronto. ABC Print Inc. receives raw material from its supplier which are located in across USA and Canada in New York, Chicago, Hamilton and Ottawa. The supplier has to select best strategy to minimize the capacity management cost while satisfying demand. Additional constraint is that if the shipment crosses the border and if there is disruption at that particular scenario, then there is a 90 % extra cost incurred due to disruption. Each time period has two scenarios; Morning, Night. As per Kyoto Protocol, each supplier has to limit its production such that the total emission caused is less than permissible value by law.

Requirement is to develop Integer Linear Programming Model which would:

1.   Allow ABC Print Inc. to allocate suppliers to its facilities i.e. decide which supplier should ship what quantity to respective facilities.

2.   Allow each supplier to know the optimized production schedule i.e. decision regarding what quantity to be produced and shipped in which time period

3.   To use aggregate capacity management and determine appropriate economic strategy i.e allow suppliers to know in advance how much capacity they will need to satisfy the customer demand in corresponding time period.

4.   Allow ABC Print Inc. to know total cost of their supply chain.

Sometimes ABC Print Inc. is experiencing abrupt change in its demand. This happens due to most unlikely instances like following reasons:

1. Very high quantity of raw material required due to technical difficulties like machine breakdowns

2. Last moment increase in customer demand without prior notice.

In such cases as-well the suppliers should be flexible enough to provide ABC Print Inc with good service level. Developed model works fine and satisfies these requirements.

3. Bullwhip effect

Following is the data file used to check abrupt changes in customer demand:

P_s: [0.5, 0.5]

es: [0.9, 0.9]

cap: [50, 60, 70]

$\widehat{H}_j$: [500, 60, 70, 70]

$h_{i,t}$: [600, 20, 30, 40, 50, 60, 70, 80]

$a_{j,k,t}$: [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]

$\overline{a}_{j,k,t}$: [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]

$d_{j,i,t}$:[1 ,2 ,3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 1 2, 3, 4, 5, 6, 7, 8, 9, 10 11, 12, 1, 2, 3, 4 ,5, 6, 31, 32]

Table 14: $Z_{j,i,s,t}$ values_time1_demand rate

				Customer (i)			
	Time Period	**Scenario**	Windsor	London	Detroit	Toronto
		(Disruption)	1	2	3	4
	$t=1$	$S=2$		$Z_{t,s,j,i}$		
Facility (j)	1 New York	1	z(1,1,1,1)=300	z(1,1,1,2)=10	z(1,1,1,3)=0	z(1,1,1,4)=0
		2	z(1,2,1,1)=230	z(1,2,1,2)=10	z(1,2,1,3)=0	z(1,2,1,4)=0
	2 Chicago	1	z(1,1,2,1)=0	z(1,1,2,2)=0	z(1,1,2,3)=0	z(1,1,2,4)=0
		2	z(1,2,2,1)=0	z(1,2,2,2)=0	z(1,2,2,3)=0	z(1,2,2,4)=0
	3 Hamilton	1	z(1,1,3,1)=0	z(1,1,3,2)=0	z(1,1,3,3)=0	z(1,1,3,4)=0
		2	z(1,2,3,1)=0	z(1,2,3,2)=0	z(1,2,3,3)=0	z(1,2,3,4)=0
	4 Ottawa	1	z(1,1,4,1)=0	z(1,1,4,2)=0	z(1,1,4,3)=15	z(1,1,4,4)=20
		2	z(1,2,4,1)=70	z(1,2,4,2)=0	z(1,2,4,3)=15	z(1,2,4,4)=20
		Demand	600	20	30	40

Table 15: $Z_{j,i,s,t}$values_time2_demand rate

			Customer (i)			
	Time Period	**Scenario (Disruption)**	Windsor	London	Detroit	Toronto
			1	2	3	4
	$t = 2$	$S = 2$	$Z_{t,s,j,i}$			
Facility (j) 1	New York	1	z(2,1,1,1)=0	z(2,1,1,2)=0	z(2,1,1,3)=0	z(2,1,1,4)=0
		2	z(2,2,1,1)=0	z(2,2,1,2)=10	z(2,2,1,3)=0	z(2,2,1,4)=0
2	Chicago	1	z(2,1,2,1)=0	z(2,1,2,2)=0	z(2,1,2,3)=0	z(2,1,2,4)=0
		2	z(2,2,2,1)=0	z(2,2,2,2)=0	z(2,2,2,3)=0	z(2,2,2,4)=0
3	Hamilton	1	z(2,1,3,1)=25	z(2,1,3,2)=30	z(2,1,3,3)=35	z(2,1,3,4)=40
		2	z(2,2,3,1)=25	z(2,2,3,2)=20	z(2,2,3,3)=35	z(2,2,3,4)=40
4	Ottawa	1	z(2,1,4,1)=0	z(2,1,4,2)=0	z(2,1,4,3)=0	z(2,1,4,4)=0
		2	z(2,2,4,1)=0	z(2,2,4,2)=0	z(2,2,43)=0	z(2,2,4,4)=0
		Demand	50	60	70	80

Decision variables $y_{j,k,t}$ values:

Table 16: $y_{j,k,t}$ values_demand rate

T	capacities	V	$y_{j,k,t}$
1	1	1	1
1	1	3	1
1	1	4	1
2	1	3	1

Result Analysis: If we look at the customer demand in data file we come to know that demand follows a uniform discrete distribution and ranges between of 0-100. However, due to unexpected reasons there is an abrupt change in demand for customer at Windsor in time period=1 and customer demand shoots up to 600. From reading the $y_{j,k,t}$ parameter we can infer that in order to satisfy the sudden rise in customer demand facilities New York, Hamilton, Ottawa go for overtime for shift 1.

❖ Total cost of objective function is 17123 $

4.8   Cost Comparison

Fig 4 explains the comparison between the supply chain costs (objective function value) incurred for all three test cases, namely; aggregate planning, more disruption, and no border between USA-Canada. In order to compare, for each test case the data file used is the same. Looking at the costs comparison graph we can infer that when the cross border disruption is more the maximum cost is incurred for the designed supply chain network. This value is 7349. When the border is not present then there is no disruption related to cross border and hence the cost of entire supply chain largely decreases. This value is 7000. The cost incurred in the aggregate planning is 7163 which is between the other two cases discussed. The graph proves that more disruption at the cross border is directly proportional to increase in supply chain cost. Similarly, the absence of border between the USA- Canada is directly proportional to decrease in supply chain cost.
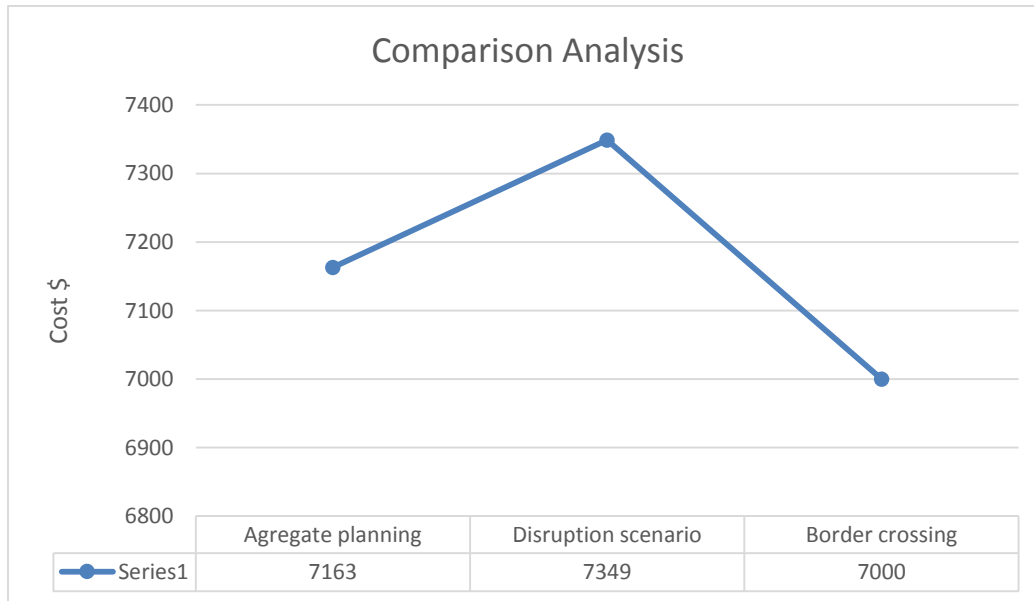
Comparison Analysis

	Agregate planning	Disruption scenario	Border crossing
Series1	7163	7349	7000

Figure 4 Comparison Analysis

5   Simulated annealing

5.1   Definition

Simulated annealing is a local search meta-heuristic used to address discrete and continuous optimization problems. The main feature of simulated annealing is that it provides a means to escape local optima by allowing hill-climbing moves (i.e., moves which worsen the objective function value) in hopes of finding a global optimum.

What are Meta –Heuristics?

In mathematical optimization, a Meta-heuristic is a higher level procedure or heuristic designed to find, generate, or select a heuristic that may provide a sufficiently good solution to an optimization problem, especially with incomplete or imperfect information or limited computation capacity. Meta-heuristics sample a set of solutions which is too large to be completely sampled. Meta-heuristics may make few assumptions about the optimization problem being solved, and so they may be usable for a variety of problems.

Compared to optimization algorithms and iterative methods, meta-heuristics do not guarantee that a globally optimal solution can be found on some non-deterministic polynomial hard class of problems. Many meta-heuristics implement some form of stochastic optimization, so that the solution found is dependent on the set of random variables generated. By searching over a large set of feasible solutions, meta-heuristics can often find good solutions with less computational effort than simple heuristics.

5.2   Working Principle of SA

Simulated annealing is so named because of its analogy to the process of physical annealing with solids, in which a crystalline solid is heated and then allowed to cool very slowly until it achieves its most regular possible crystal lattice configuration (i.e., its minimum lattice energy state), and thus is free of crystal defects. If the cooling schedule is sufficiently slow, the final configuration results in a solid with such superior structural integrity. Simulated annealing establishes the connection between this type of thermodynamic behavior and the search for global minima for a discrete optimization problem.

Furthermore, it provides an algorithmic means for exploiting such a connection. At each iteration of a simulated annealing algorithm applied to a discrete optimization problem, the objective function generates values for two solutions (the current solution and a newly selected solution) are compared. Improving solutions are always accepted; while a fraction of non-improving (inferior) solutions are accepted in the hope of escaping local optima in search of global optima. The probability of accepting non-improving solutions depends on a temperature parameter, which is typically non-increasing with each iteration of the algorithm.

The key algorithmic feature of simulated annealing is that it provides a means to escape local optima by allowing hill-climbing moves (i.e., moves which worsen the objective function value). As the temperature parameter is decreased to zero, hill-climbing moves occur less frequently, and the solution distribution associated with the inhomogeneous Markov chain that models the behavior of the algorithm converges to a form in which all the probability is concentrated on the set of globally optimal solutions (provided that the algorithm is convergent, otherwise the algorithm will converge to a local optimum, which may or not be globally optimum. The above discussed working principle of simulated annealing had been taken from the book "Hand book of Meta heuristics, 2003" written by Kochenberger and Glover.
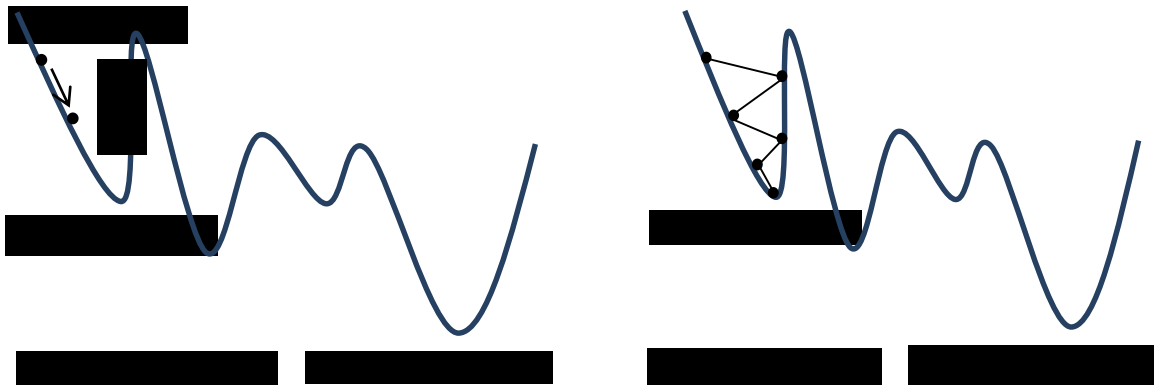
Figure 5 Simulated annealing graphical representation

5.3   Generic Simulated Annealing Algorithm Steps

Step1: Declare all parameters. Enter initial solution, initial temperature *(Tin),*

minimum temperature *(Tmin),* number of iterations *(N)* and cooling rate (*CR).*

Step 2: Calculate the energy for the initial configuration *(Ec).*

Step 3: Execute outer loop

Step 4: Execute inner loop by setting the value of n=0.

    Step 4.1: Develop a neighboring solution and calculate new energy (En).

    Step 4.2: IF new energy is less than current energy, proceed to 6.

       ELSE

       IF metropolis criterion is satisfied, proceed to 4.4.

          ELSE

             Step 4.3: Increment the value of n (n=n+1). Proceed to

              Step 4.5.

    Step 4.4: New state = Current state (En=Ec). Increment the value of n (n=n+1).

    Step 4.5: IF n<=N, go to Step 3.1

      ELSE T=CR*T

        IF T<= Tmin, declare final solution. ELSE Go to step 4.
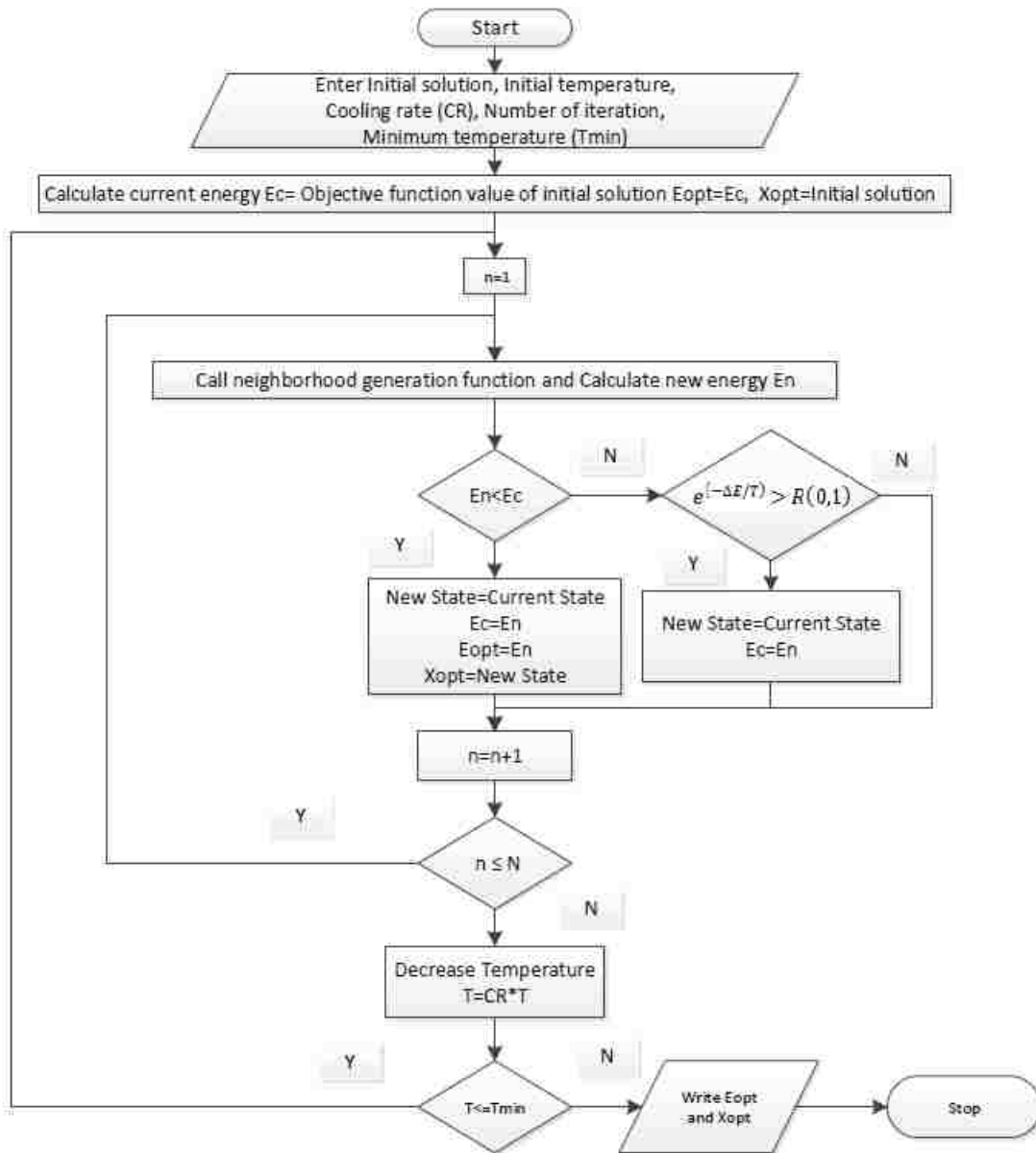
  UNTIL Stopping criterion is reached.

Figure 6 SA Algorithm flowchart

5.4   Initial Solution Generation

Algorithm Steps for initial solution are as follows:

Step 1: Initialize all parameters like total number of Capacities, customers, facilities, time periods, the Cooling rate, initial starting temperature, cost of each carbon credit(alpha), Total permissible emission per facility(omega), inner loop iteration count

Step 2: Generate decision variables $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ randomly. Ensure constraint   4,5,6,7,9,10 are all satisfied when generating these two decision variables.

Step 3: Generate $\hat{y}_{j,k,t}$ randomly such that for all $t \in T$, $k \in K$, $j \in V$, $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ are not 1 . This condition ensures that a facility cannot be constructed and dismantled at the same time.

Step 4: Use the above randomly generated decision variable values to calculate $Z_{j,i,s,t}$.   Use the decision variables and input them as parameter in the linear   programming math model to obtain the decision variable $Z_{j,i,s,t}$. The model solves for optimal values of $Z_{j,i,s,t}$ given the decision variables

Step 5: Use this $Z_{j,i,s,t}$ $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ as one initial feasible solution for simulated annealing
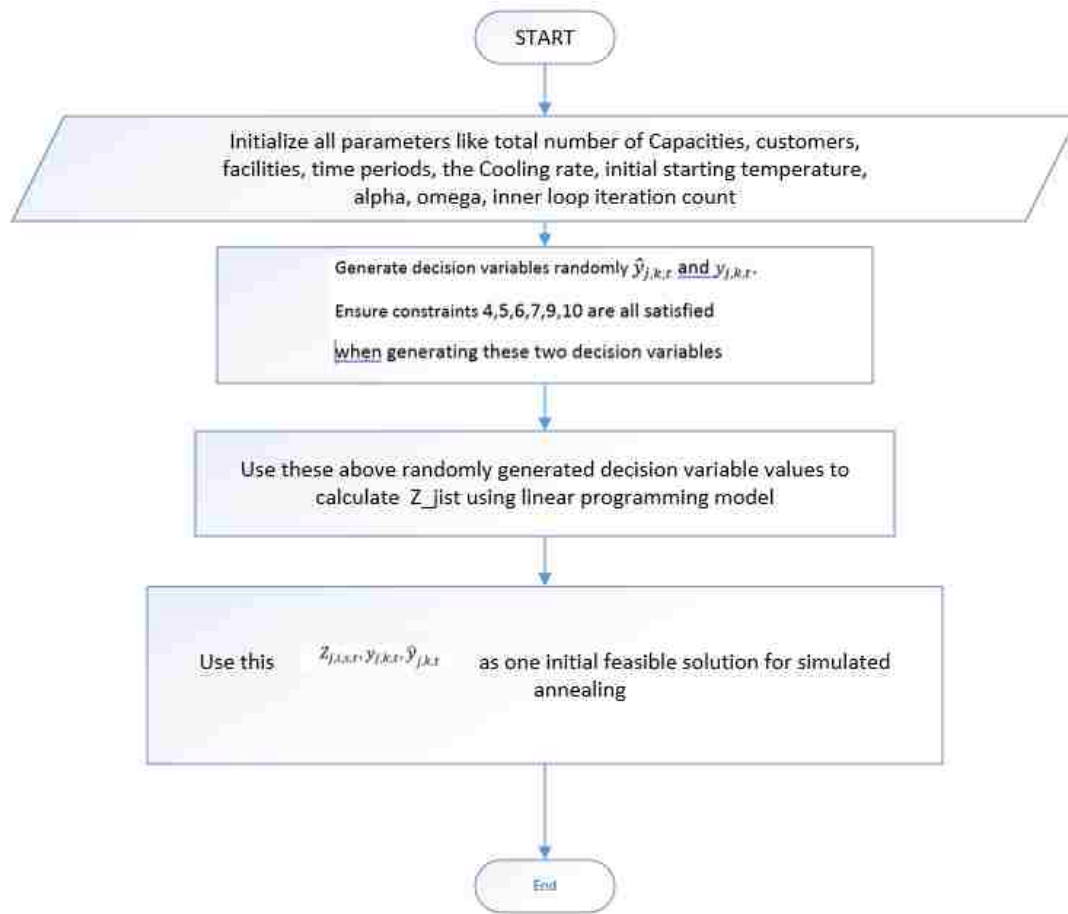
Flow chart for Initial Solution

Figure 7 Initial Solution Algorithm flowchart

5.5   Neighborhood Generation Function

Algorithm Steps for generating neighborhood solution are as follows:

Step 1: Initialize all parameters like total number of capacities, customers, facilities, time periods, cooling rate, initial starting temperature, alpha, omega, inner loop iteration counter *(M)*

Step 2: Assign the $Z_{j,i,s,t}$, $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ values obtained from initial solution to

      Current $Z_{j,i,s,t}$, $y_{j,k,t}$ and $\hat{y}_{j,k,t}$

Assign the following

      bestsofar_$y_{j,k,t}$ = current_$y_{j,k,t}$

      bestsofar_$\hat{y}_{j,k,t}$ = current_$\hat{y}_{j,k,t}$

      bestsofar_$Z_{j,i,s,t}$, = current_$Z_{j,i,s,t}$,

      Lastly, assign the value of the objective function obtained from initial solution to current objective function

Step 4: Assign the current objective function value to best_so_far objective function value.

Step 5: Apply while loop such that while (temperature >1) proceed to next step else print

      bestsofar_$y_{j,k,t}$ = current_$y_{j,k,t}$

      bestsofar_$\hat{y}_{j,k,t}$ = current_$\hat{y}_{j,k,t}$

      bestsofar_$Z_{j,i,s,t}$, = current_$Z_{j,i,s,t}$,

      Ebs= Ec

Step 6: Check the counter *n*. If the n is less than the inner loop iteration counter *M* then proceed to next step else decrease the temperature with respect to cooling rate and go to Step 5

Step 7: Apply swap operator to generate neighborhood scheme

Step 8: Check if for any facility for any year the production is negative. If all production values are positive accept the output else apply production repair function.

Step 9: Check if the emission constraint is satisfy. If emission constraint is unsatisfied apply the emission repair function else proceed to next step.

Step 10: Check if constraint 1 is satisfied. If unsatisfied apply demand repair function else go to next step.

Step 11: Check if constraint 2 is satisfied. If it is unsatisfied apply production repair function else go to next step.

Step 12: Calculate the current value of the current objective function (Ec)

Step 13: Calculate the value of the Neighborhood objective function (En)

Step 14: Check if the En < Ec then go to next step else go to Step 17

Step 15: $Current\_Z_{j,i,s,t}= Neighborhood\_Z_{j,i,s,t}$

$Current\_y_{j,k,t}= Neighborhood\_y_{j,k,t}$

$Current\_\hat{y}_{j,k,t}= Neighborhood\_\hat{y}_{j,k,t}$

$best\_so\_far\_Z_{j,i,s,t}=Current\_Z_{j,i,s,t}$

$best\_so\_far\_y_{j,k,t}=Current\_y_{j,k,t}$

$best\_so\_far\_\hat{y}_{j,k,t}= Current\_\hat{y}_{j,k,t}$

Ec = En

Ebs = Ec

Step 16: Calculate $e^{-(En-Ec)/Temperature}$. Generate a random number between 0-1.

Step 17: Check if $e^{-(En-Ec)/Temperature}$ > random number then do

$Current\_Z_{j,i,s,t}= Neighborhood\_Z_{j,i,s,t}$

$Current\_y_{j,k,t}= Neighborhood\_y_{j,k,t}$

58

$$Current\_\hat{y}_{j,k,t} = Neighborhood\_\hat{y}_{j,k,t}$$

Ec=En   Else go to Step 6

Flow chart for Neighborhood Function is shown in Figure 8.

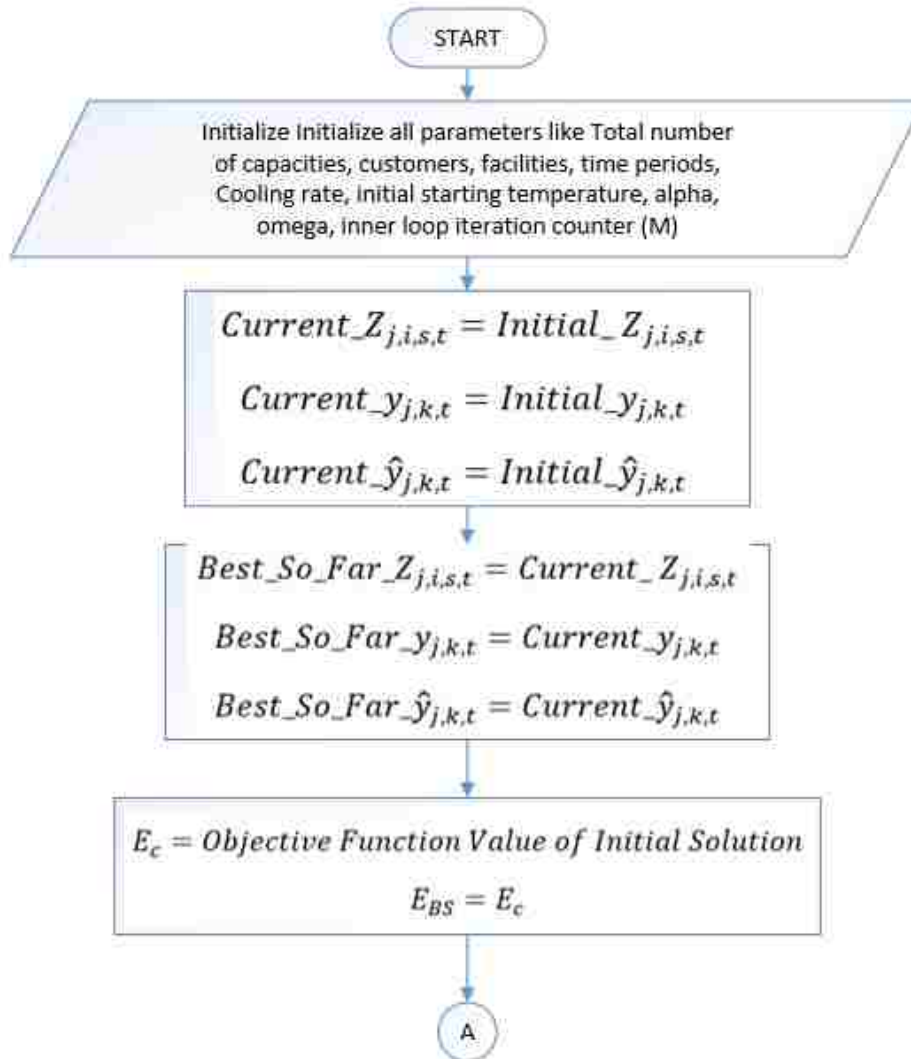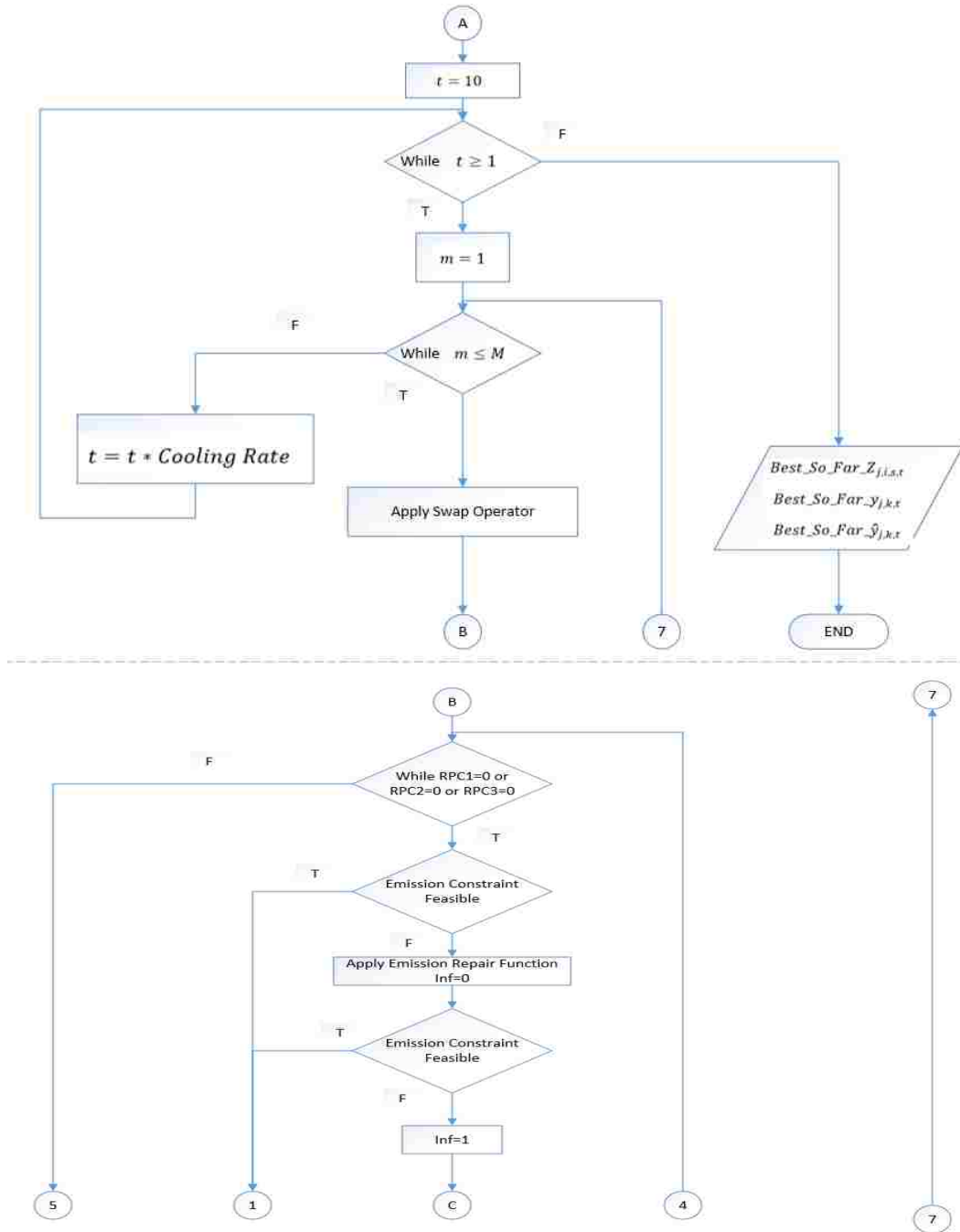*Figure 8 Neighborhood algorithm flow chart*

A

$t = 10$

While $t \geq 1$
F
T

$m = 1$

F
While $m \leq M$
T

$t = t * Cooling\ Rate$

Apply Swap Operator

$Best\_So\_Far\_Z_{j,i,s,t}$
$Best\_So\_Far\_y_{j,k,t}$
$Best\_So\_Far\_\hat{y}_{j,k,t}$

B

7

END

B

7

While RPC1=0 or RPC2=0 or RPC3=0
F

T

Emission Constraint Feasible
T

F

Apply Emission Repair Function Inf=0

Emission Constraint Feasible
T

F

Inf=1

5

1
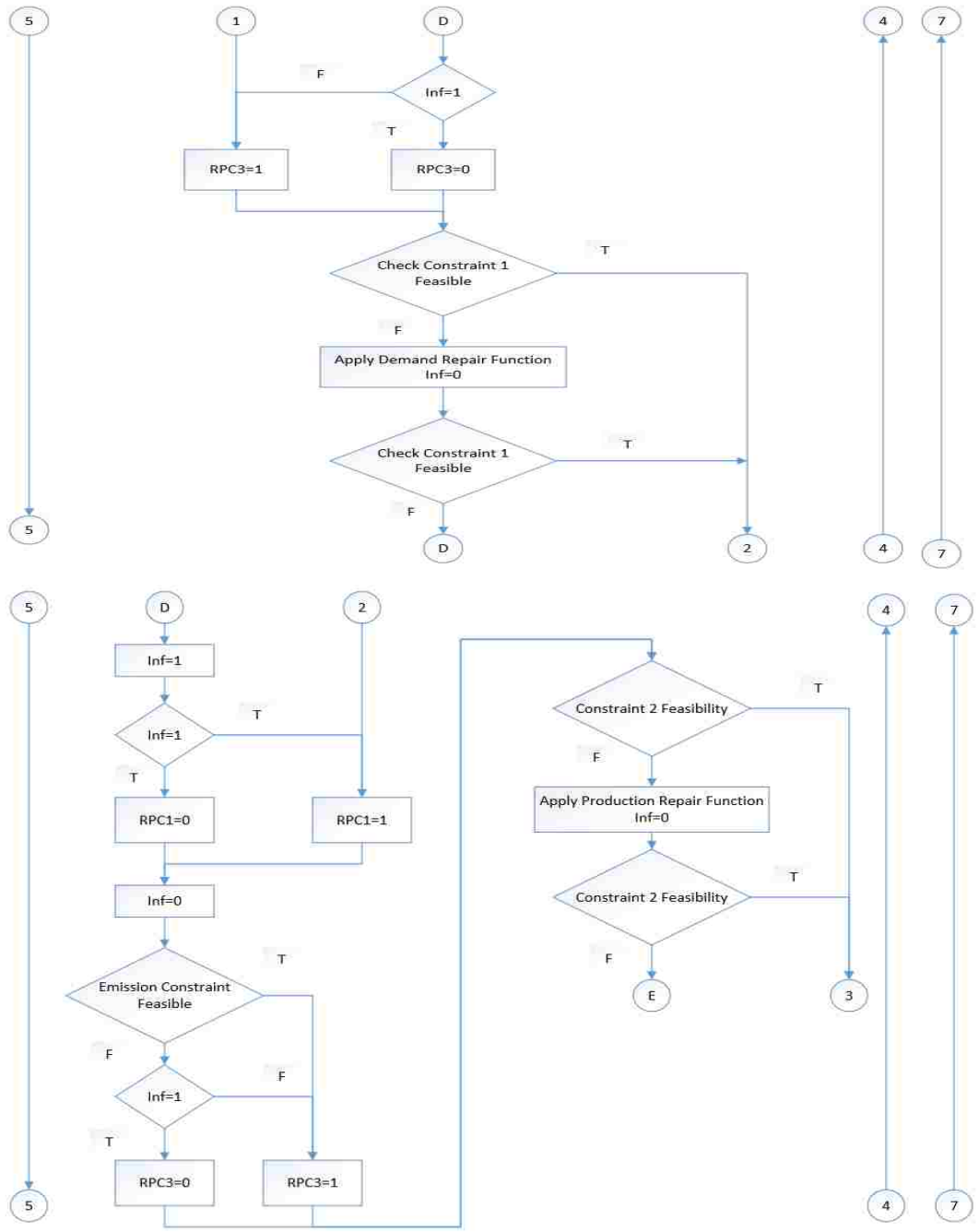
C

4

7

Figure 9 neighborhood flow chart continued
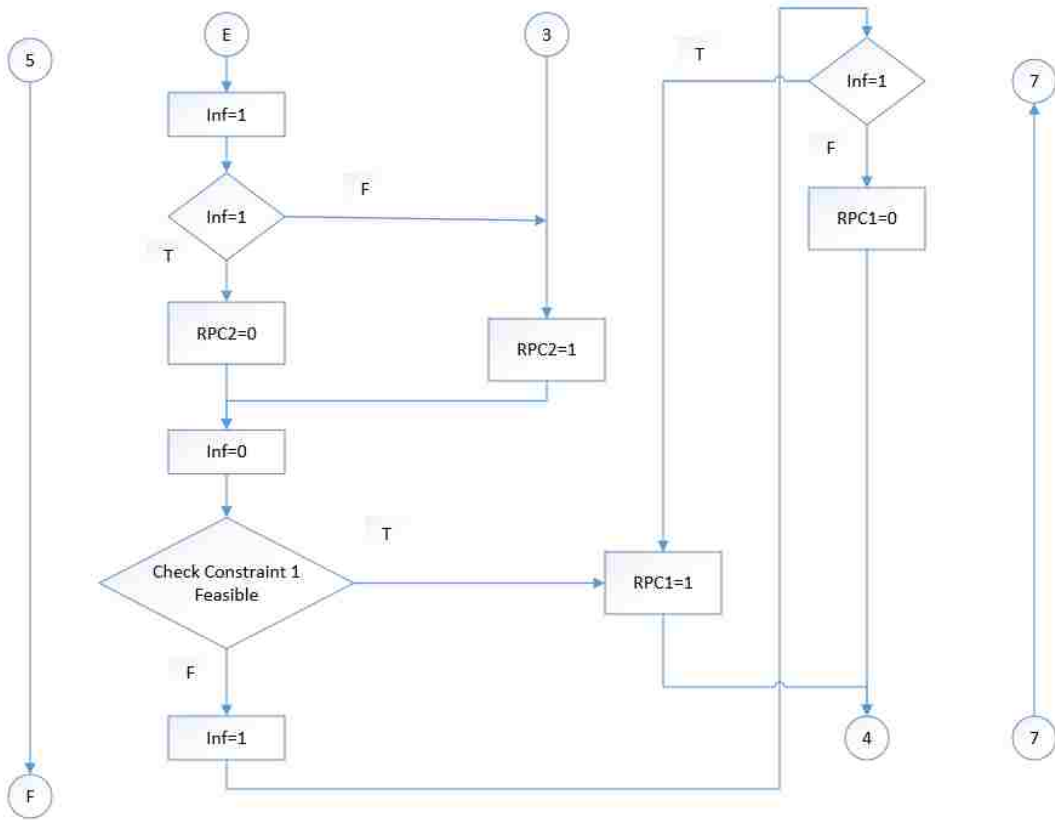
60

Figure 10 flow chart continued

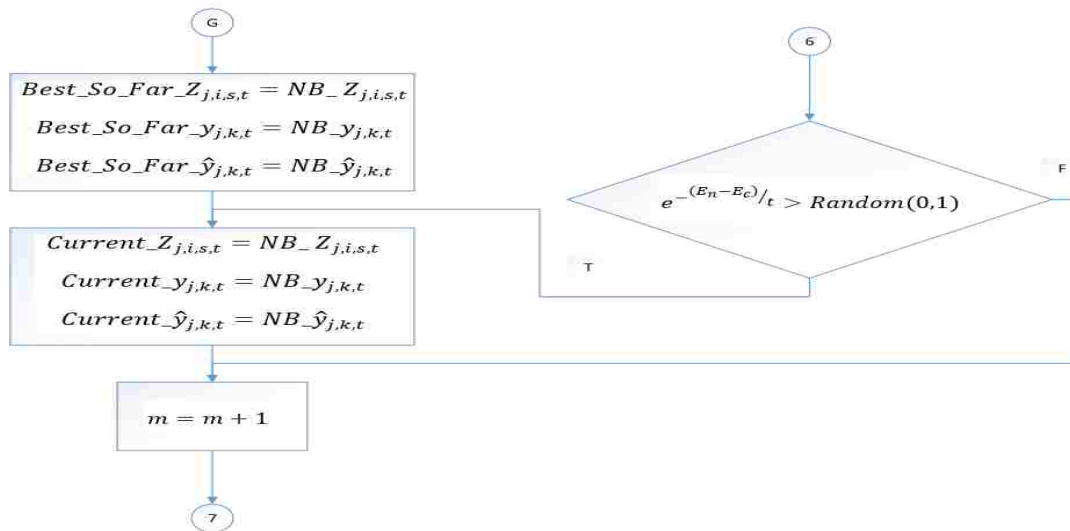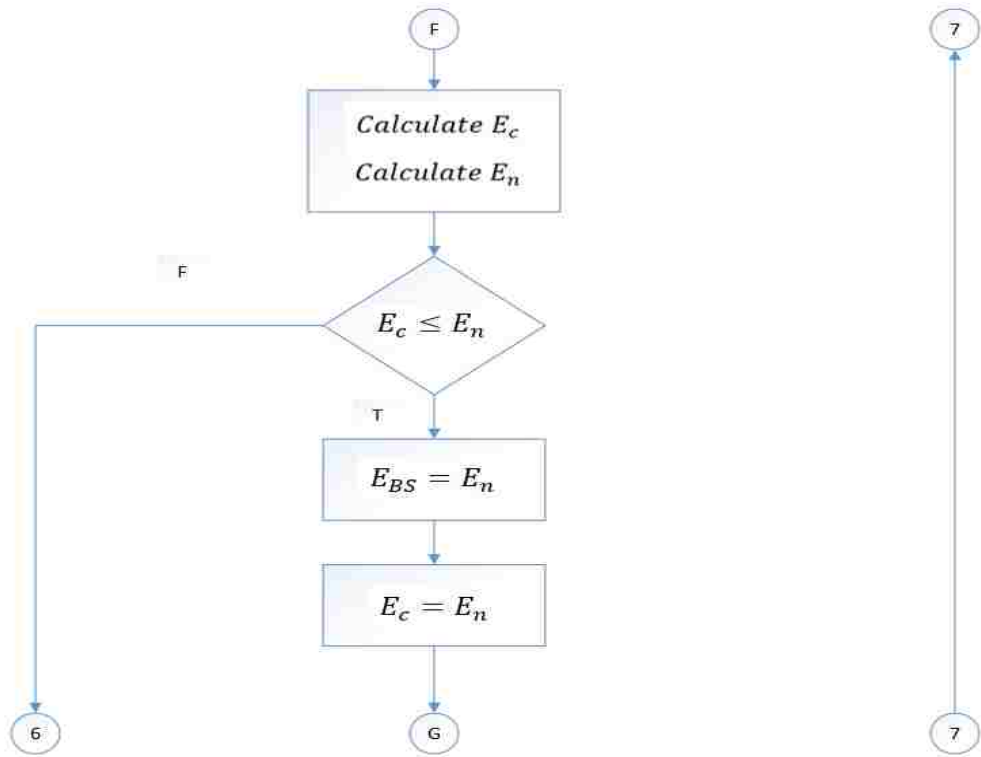*Figure 11 Neighborhood flow chart continued*

Figure11 Neighborhood flow chart (continued)

5.6   Explanation

1. $y_{j,k,t}$ Decision variable generation procedure

The constraint ensures that for every time period and for every facility across all capacities at most one capacity is constructed. For example, please refer the below output of decisions variable $y_{j,k,t}$.

As shown in tables 17 and 18, $y_{j,k,t}$ values, in Time periods $t = 1$ there is at-most on capacity constructed for each facility.

Table 17   y_(j,k,t) values in constraint 5

Time Period $(t = 1)$		Capacity (k)		
		1	2	3
	1	$y_{j,k,t}(1,1,1) = 1$	$y_{j,k,t}(1,2,1) = 0$	$y_{j,k,t}(1,3,1) = 0$
Facility (j)	2	$y_{j,k,t}(1,1,2) = 0$	$y_{j,k,t}(1,2,2) = 1$	$y_{j,k,t}(1,3,2) = 0$
	3	$y_{j,k,t}(1,1,3) = 1$	$y_{j,k,t}(1,2,3) = 0$	$y_{j,k,t}(1,3,3) = 0$
	4	$y_{j,k,t}(1,1,4) = 1$	$y_{j,k,t}(1,2,4) = 0$	$y_{j,k,t}(2,3,4) = 0$

Table 18   y_(j,k,t) values in constraint 5

Time Period $(t = 2)$		Capacity (k)		
		1	2	3
	1	$y_{j,k,t}(2,1,1) = 0$	$y_{j,k,t}(2,2,1) = 1$	$y_{j,k,t}(2,3,1) = 0$
Facility (j)	2	$y_{j,k,t}(2,1,2) = 0$	$y_{j,k,t}(2,2,2) = 0$	$y_{j,k,t}(2,3,2) = 1$
	3	$y_{j,k,t}(2,1,3) = 0$	$y_{j,k,t}(2,2,3) = 1$	$y_{j,k,t}(2,3,3) = 0$
	4	$y_{j,k,t}(2,1,4) = 1$	$y_{j,k,t}(2,2,4) = 0$	$y_{j,k,t}(2,3,4) = 0$

2. $\hat{y}_{j,k,t}$ Decision variable generation procedure

This constraint is designed to ensure that at most one capacity can be dismantled for each facility in each time period. Hence, to avoid that we restrict the random generation of $\hat{y}_{j,k,t}$ such that at-most only one capacity can be dismantled in any time for any facility. Tables 19 and 20 illustrates the conditionally generated $\hat{y}_{j,k,t}$, $\forall\ j \in\ V, t \in T$.

Table 19 ŷ_(j,k,t) values as per constraint 4

Time Period ($t = 1$)		Capacity (k)		
		1	**2**	**3**
Facility (j)	1	$\hat{y}_{j,k,t}(1,1,1) = 0$	$\hat{y}_{j,k,t}(1,2,1) = 1$	$\hat{y}_{j,k,t}(1,3,1) = 0$
	2	$\hat{y}_{j,k,t}(1,1,2) = 1$	$\hat{y}_{j,k,t}(1,2,2) = 0$	$\hat{y}_{j,k,t}(1,3,2) = 0$
	3	$\hat{y}_{j,k,t}(1,1,3) = 0$	$\hat{y}_{j,k,t}(1,2,3) = 0$	$\hat{y}_{j,k,t}(1,3,3) = 1$
	4	$\hat{y}_{j,k,t}(1,1,4) = 0$	$\hat{y}_{j,k,t}(1,2,4) = 0$	$\hat{y}_{j,k,t}(1,3,4) = 1$

Table 20 ŷ_(j,k,t) values as per constraint 4

Time Period ($t = 2$)		Capacity (k)		
		1	**2**	**3**
Facility (j)	1	$\hat{y}_{j,k,t}(2,1,1) = 0$	$\hat{y}_{j,k,t}(2,2,1) = 0$	$\hat{y}_{j,k,t}(2,3,1) = 0$
	2	$\hat{y}_{j,k,t}(2,1,2) = 1$	$\hat{y}_{j,k,t}(2,2,2) = 0$	$\hat{y}_{j,k,t}(2,3,2) = 0$
	3	$\hat{y}_{j,k,t}(2,1,3) = 0$	$\hat{y}_{j,k,t}(2,2,3) = 0$	$\hat{y}_{j,k,t}(2,3,3) = 0$
	4	$\hat{y}_{j,k,t}(2,1,4) = 0$	$\hat{y}_{j,k,t}(2,2,4) = 1$	$\hat{y}_{j,k,t}(2,3,4) = 0$

Additionally, there is another condition. At any particular instance both decision variables cannot take value =1. Reason being, $y_{j,k,t}$ stands for capacity construction and $\hat{y}_{j,k,t}$ stands for capacity dismantling. Both capacity construction and dismantling cannot take place at the same time. The Tables 21 and 22 represent the $y_{j,k,t}$ values of the corresponding run. By making comparison between Tables 19-21, and 20-22, we can see that there is no single instance where both $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ are 1.

Table 21 y_(j,k,t) values

Time Period ($t = 1$)		Capacity (k)		
		1	**2**	**3**
Facility (j)	1	$y_{j,k,t}(1,1,1) = 1$	$y_{j,k,t}(1,2,1) = 0$	$y_{j,k,t}(1,3,1) = 0$
	2	$y_{j,k,t}(1,1,2) = 0$	$y_{j,k,t}(1,2,2) = 1$	$y_{j,k,t}(1,3,2) = 0$
	3	$y_{j,k,t}(1,1,3) = 1$	$y_{j,k,t}(1,2,3) = 0$	$y_{j,k,t}(1,3,3) = 0$
	4	$y_{j,k,t}(1,1,4) = 1$	$y_{j,k,t}(1,2,4) = 0$	$y_{j,k,t}(2,3,4) = 0$

Table 22 y_(j,k,t) values

Time Period ($t = 2$)		Capacity (k)		
		1	**2**	**3**
Facility (j)	1	$y_{j,k,t}(2,1,1) = 0$	$y_{j,k,t}(2,2,1) = 1$	$y_{j,k,t}(2,3,1) = 0$
	2	$y_{j,k,t}(2,1,2) = 0$	$y_{j,k,t}(2,2,2) = 1$	$y_{j,k,t}(2,3,2) = 1$
	3	$y_{j,k,t}(2,1,3) = 0$	$y_{j,k,t}(2,2,3) = 1$	$y_{j,k,t}(2,3,3) = 0$
	4	$y_{j,k,t}(2,1,4) = 0$	$y_{j,k,t}(2,2,4) = 0$	$y_{j,k,t}(2,3,4) = 1$

3. RHS repair function

This repair function is designed to achieve a positive production value for each facility each year. In the developed math model production is calculated using below term:

$$RHS = \widehat{H}_j + \sum_{t' \le t} \sum_{k \in K} y_{j,k,t'} H_k - \sum_{t' \le t} \sum_{k \in K} \hat{y}_{j,k,t} H_k \qquad (1)$$

For simplicity, let's call this term as RHS. Now, the decision variables $\hat{y}_{j,k,t}$ and $y_{j,k,t}$ generated randomly and are inserted in RHS. This gives the production for each facility each year.

In case if the RHS / production for that particular facility for that year becomes negative, it may lead to infeasible solution.

To avoid this negative production values, RHS repair function has been designed. Please find the flow chart for RHS repair function in Appendix flow chart.

4. Swap operator

This operator is designed to generate neighborhood function. Neighborhood function generation first begins with randomly selecting any two decision variables from all available neighborhood $y_{j,k,t}$ and then switching there values. Here, we ensure that the two selected facilities are not same .Let's say we selected two $y_{j,k,t}$ values:

- If their values are equal to 1 and 0 then we apply the swap operator and change it to 0(dismantle it) and 1(construct)
- If their values are equal to 0 and 1 then we apply the swap operator and change it to 1(construct) and 0(dismantle it).
- If both selected values are 0, then we construct for one.
- If both selected values are 1, then we dismantle for one.

Lastly, we also change the corresponding $\hat{y}_{j,k,t}$ by ensuring that $\hat{y}_{j,k,t}$ and $y_{j,k,t}$ are not 1 at the same. Additionally, the neighborhood function ensures that after the swap operator, constraint 4 and 5 are not violated. If constraint 5 is violated then all $y_{j,k,t}$ values, except the swapped one, for that facility in that time period are turned 0(dismantled). Similarly, if constraint 4 is violated

then all $\hat{y}_{j,k,t}$, except the swapped one, for that facility in that time period are turned 0(dismantled). Since the binary decision variables generated are huge, this operator explores a larger search space thus increasing the efficiency of the designed algorithm.

Table 23 represents $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ values before applying swap operator.

Table 23 y_(j,k,t) and ŷ_(j,k,t) values

Time Period ($t =$ 1)		Capacity (k)		
		1	**2**	**3**
Facility (j)	**1**	$y_{j,k,t}(1,1,1) = 0$ $\hat{y}_{j,k,t}(1,1,1) = 1$	$y_{j,k,t}(1,2,1) = 1$ $\hat{y}_{j,k,t}(1,2,1) = 0$	$y_{j,k,t}(1,3,1) = 0$ $\hat{y}_{j,k,t}(1,3,1) = 0$
	2	$y_{j,k,t}(1,1,2) = 0$ $\hat{y}_{j,k,t}(1,1,2) = 1$	$y_{j,k,t}(1,2,2) = 1$ $\widehat{y}_{j,k,t}(1,2,2) = 0$	$y_{j,k,t}(1,3,2) = 0$ $\hat{y}_{j,k,t}(1,3,2) = 0$
	3	$y_{j,k,t}(1,1,3) = 1$ $\hat{y}_{j,k,t}(1,1,3) = 0$	$y_{j,k,t}(1,2,3) = 0$ $\hat{y}_{j,k,t}(1,2,3) = 1$	$y_{j,k,t}(1,3,3) = 0$ $\hat{y}_{j,k,t}(1,3,3) = 0$
	4	$y_{j,k,t}(1,1,4) = 1$ $\hat{y}_{j,k,t}(1,1,4) = 0$	$y_{j,k,t}(1,2,4) = 0$ $\hat{y}_{j,k,t}(1,2,4) = 0$	$y_{j,k,t}(2,3,4) = 0$ $\hat{y}_{j,k,t}(1,3,4) = 0$

Table 24 represents $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ values after swap operator.

Table 24 y_(j,k,t) and ŷ_(j,k,t) values

Time Period ($t =$ 1)		Capacity (k)		
		1	**2**	**3**
Facility (j)	**1**	$y_{j,k,t}(1,1,1) = 0$ $\hat{y}_{j,k,t}(1,1,1) = 1$	$y_{j,k,t}(1,2,1) = 0$ $\hat{y}_{j,k,t}(1,2,1) = 0$	$y_{j,k,t}(1,3,1) = 0$ $\hat{y}_{j,k,t}(1,3,1) = 0$
	2	$y_{j,k,t}(1,1,2) = 1$ $\hat{y}_{j,k,t}(1,1,2) = 0$	$y_{j,k,t}(1,2,2) = 0$ $\widehat{y}_{j,k,t}(1,2,2) = 0$	$y_{j,k,t}(1,3,2) = 0$ $\hat{y}_{j,k,t}(1,3,2) = 0$
	3	$y_{j,k,t}(1,1,3) = 1$ $\hat{y}_{j,k,t}(1,1,3) = 0$	$y_{j,k,t}(1,2,3) = 0$ $\hat{y}_{j,k,t}(1,2,3) = 1$	$y_{j,k,t}(1,3,3) = 0$ $\hat{y}_{j,k,t}(1,3,3) = 0$
	4	$y_{j,k,t}(1,1,4) = 1$ $\hat{y}_{j,k,t}(1,1,4) = 0$	$y_{j,k,t}(1,2,4) = 0$ $\hat{y}_{j,k,t}(1,2,4) = 0$	$y_{j,k,t}(2,3,4) = 0$ $\hat{y}_{j,k,t}(1,3,4) = 0$

After the neighborhood function is applied and new $y_{j,k,t}$ and $\hat{y}_{j,k,t}$ are obtained, it is likely that constraint 1 gets infeasible. Hence, we check and apply repair function to make it feasible.

Following are the pseudo code for repair functions used.

❖ Constraint 1 Repair Function:

$Demand = h_{i,t} \times p_s \quad \forall i \in U, s \in S, t \in T$

If $\sum_{j \in V} Z_{j,i,s,t} < h_{i,t} \times p_s$ then

$$Diff = Ceil(h_{i,t} \times p_s) - \sum_{j \in V} Z_{j,i,s,t}$$

Ratio= $Diff$/ Total number of facilities

While ($Diff$>0) do

For all ($j \in V$) do

$Z_{j,i,s,t}$= $Z_{j,i,s,t} + ratio$

End-do

$$Diff = Ceil(h_{i,t} \times p_s) - \sum_{j \in V} Z_{j,i,s,t}$$

Ratio= $Diff$/ Total number of facilities

End-do

End-if

❖ Constraint 2 Repair Function:

Production= $\widehat{H}_j + \sum_{t' \leq t} \sum_{k \in K} y_{j,k,t'} H_k - \sum_{t' \leq t} \sum_{k \in K} \hat{y}_{j,k,t} H_k$

forall ($j \in V$, t $\in T$)do

if ($\sum_{i \in U} \sum_{s \in S} Z_{j,i,s,t}$ > Production) then

Difference = $\sum_{i \in U} \sum_{s \in S} Z_{j,i,s,t}$ - production

Ratio=ceil[Difference/ (scenarios *customers)]

While (Difference >0) do

for all (i $\in U$, s $\in S$) do

If ($Z_{j,i,s,t}$ > Difference) then

$$Z_{j,i,s,t} = ceil(Z_{j,i,s,t} - ratio)$$

End-if

End-do

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$$\text{Difference} = \sum_{i \,\epsilon\, U} \sum_{s \,\epsilon\, S} Z_{j,i,s,t} \;-\; \text{production}$$

Ratio= [Difference/ (scenarios *customers)]

End-do

End-if
End-do

❖ Constraint 3 Repair Function:

forall ($j \;\epsilon\; V$, t $\in T$)do

$\text{emission} = \sum_{i \,\epsilon\, U} \sum_{s \,\epsilon\, S} Z_{j,i,s,t}$ * e

if (emission > omega) then
    difference = omega – emission
    ratio = [difference / (customers*scenarios)]
    while (difference >0)do
        for all (i $\in$ U, s $\in$ S) do

            If ($Z_{j,i,s,t}$ > Difference) then

$$Z_{j,i,s,t} = \text{ceil}(Z_{j,i,s,t} - \text{ratio})$$

            End-if

        End-do

$$\text{Difference} = \sum_{i \,\epsilon\, U} \sum_{s \,\epsilon\, S} Z_{j,i,s,t} \;-\; \text{production}$$

Ratio=[Difference/ (scenarios *customers)]

    End-do
  End-if
End-do

5.7. SA Test Case

5.7.1 Test Case 1

Table 25 SA Test case 1 size

Problem Size	Qty
Facilities	4
Customers	4
Scenarios	2
Time	2
Capacities	3

Table 26 SA Test case 1 results

Math Model Objective value: 7083

	SA	Number of inner loop iterations = 30		
No	Objective value	Error	Error Gap Percentage	Computation Time(seconds)
1	7368.3	285.3	4.027954257	1
2	7370.3	287.3	4.05619088	2
3	7589.1	506.1	7.145277425	2
4	7334	251	3.543696174	2
5	7283.9	200.9	2.83636877	2
6	7185.1	102.1	1.441479599	2
7	7493.5	410.5	5.79556685	2
8	7274.1	191.1	2.698009318	2
9	7170	87	1.228293096	1
10	7246.6	163.6	2.309755753	2
Average	7331.49	248.49	3.50%	Std. 1.761971

5.7.2 Test Case 2

Table 27 SA Test case 2 size

Size of Problem	Qty
Facilities	8
Customers	8
Scenarios	4
Time	4
Capacities	5

Table 28 SA Test case 2 results

Math Model Objective value: 30473.4

	SA	Number of inner loop iterations = 100			
No	Objective value	Initial Solution Objective Value	Error	Error Gap Percentage	Computation Time(seconds)
1	31991	47294.1	1517.6	4.980080989	40
2	31880.6	48556.5	1407.2	4.617797817	42
3	31754.1	48797.3	1280.7	4.202681683	45
4	32103.7	47762.6	1630.3	5.349911726	50
5	32263.3	48454.4	1789.9	5.873647181	42
6	31958.3	48654.2	1484.9	4.872774288	43
7	32187.1	48817.1	1713.7	5.623593035	44
8	32188.1	48967.1	1714.7	5.626874586	40
9	32312	49915.1	1838.6	6.033458689	42
10	32486.5	48254.2	2013.1	6.606089245	45
Average	32112.47		1639	5.37%	Std. 0.684062

5.7.3 Test Case 3

Table 29 SA Test case 3 size

Size of Problem	Qty
Facilities	10
Customers	10
Scenarios	5
Time	5
Capacities	8

Table 30 SA Test case 3 results

Math Model Objective value: 82348.1					
	SA	Number of inner loop iterations = 200			
No	Objective value	Initial Solution Objective Value	Error	Error Gap Percentage	Computation Time(min)
1	89377.1	159179	7029	8.535716064	10
2	88786.8	158885	6438.7	7.818881067	11
3	89563.1	159738	7215	8.761586485	12
4	89388.1	158466	7040	8.549073992	10
5	88589.8	160121	6241.7	7.579652718	10
6	89513.2	159749	7165.1	8.700990065	10
7	89617.2	159623	7269.1	8.827283204	9
8	89943.8	159673	7595.7	9.223892233	8
9	89426.6	158847	7078.5	8.59582674	9
10	89368.5	159026	7020.4	8.525272593	9
Average	89357.42		7009	8.51%	Std. 0.454206

5.7.4 Test Case 4

Table 31 SA Test case 4 size

Size of Problem	Qty
Facilities	16
Customers	16
Scenarios	6
Time	6
Capacities	8

Table 32 SA Test case 4 results

Math Model Objective value: 154794

	SA	Number of inner loop iterations = 200			
No	Objective value	Initial Solution Objective Value	Error	Error Gap Percentage	Computation Time(min)
1	157763	263778	2969	1.918032999	25
2	157173	261907	2379	1.536881274	24
3	156651	263686	1857	1.199658902	25
4	156955	263075	2161	1.396048942	23
5	159133	261983	4339	2.803080223	26
6	159913	263485	5119	3.306975723	25
7	159237	261268	4443	2.870266289	28
8	156749	283574	1955	1.262968849	29
9	159949	261008	5155	3.330232438	24
10	162204	262807	7410	4.787007248	24
Average	158572		3778.7	2.46%	Std. 1.11675

5.8   Discussion

A simulated annealing (SA) based meta-heuristic has been developed to solve large scale size of the problem under consideration. A novel neighborhood generation scheme, using **swap operator,** has been used. The neighborhood solution generated explores a larger feasible solution space. Also, completely novel repair functions are designed to ensure neighborhood solution generated is feasible.

Table (33) below has the first column which shows the size of the problem for each instance. In total there are four test instances considered. For each increment in the test instance the size of the problem is increased. Under the column "math model" the value of the objective function obtained using linear programming solver is stated. In the adjacent column the value of objective function obtained using simulated annealing algorithm is mentioned. For each instance, with the same data file, problem is solved using Xpress optimizer and SA algorithm so as to compare their objective values. For testing the developed simulated annealing based meta-heuristic we ran 10 iterations for each size of problem. The initial solution used for each instance was different. Hence, the solution space explored is efficient. Taking reading for each iteration we calculated the standard deviation, error gap, average value of objective function value obtained from meta-heuristic. Following formulas are used.

$$Error = \ SA\ Result - Math\ Result$$

$$Error\ Gap\ Percentage\ (EGP) = \left({Error}/{Math\ result} \right) \times 100$$

For the fourth instance the mean error gap % is the lowest while for the third instance the error gap % is the highest. This proves that the error gap does not increase with the increase in size of the problem. On the other hand the standard deviation in the error gap is maximum for the fourth instance while it is lowest for third instance. Proposed SA obtains a solution with error gap less than 10% for all instances. This standard deviation obtained is far less compared to existing literature. Hence, the developed algorithm is proven to be suitably designed.

5.9   Result of Simulated Annealing

Table 33 SA result summary

No	Problem Size Facilities, Customer, Scenarios, time, Capacities	Mean Objective Function Math Model	SA	CPU Time (seconds) SA	Error gap Mean %	Std
1	4,4,2,2,3	7083	7331.49	3	3.50%	0.6247
2	8,8,4,4,5	30473.4	32112.5	43.3	5.37%	0.684
3	10,10,5,5,8	82348.1	89357.42	588	8.51%	0.454
4	16,16,6,6,8	154794	158572	1518	2.46%	1.116

6   Conclusion and Future Work

Use of developed model in printing Industry: As the developed model consists of use of reconfigurable manufacturing systems in each manufacturing facility (detail discussion done in literature review) it allows for high responsiveness to fluctuating customer demands. Also, with the use of RMS, mass customization is possible at the same time allowing mass production. An industry like printing needs mass production along with customization. The developed model allows each facility to determine the scale and configuration of its capacities in their installed RMS.

Use of developed model to cope up with uncertainty and risks involved in supply chain: Supply chain management systems are increasingly growing complex. Tremendous uncertainty is involved at every step of the chain network. This uncertainty leads to risk at every stage and hence managers need to make decisions under uncertain conditions. Therefore, finding risk involved, analyzing it and then developing mitigating plan is important. All departments related to supply chain such as finance, insurance, operations are integrated and hence importance of considering risk is understood by all. Wrong decisions taken due to risk causes adverse economic impact or a decrease in the performance of the business. Risk can also be defined as anything that disrupts the information, raw material or product flows delivered from original supplier to ultimate end-user. Supply chain risk and uncertainty is difficult to assess, monitor, control and difficult to incorporate in the math model. Monetary losses due to risks are loss of profit, in-efficiency due to over spending, less net present worth of the invested amount, loss of customer good will and

satisfaction, wrong supplier selection. Our developed model solves for optimal quantity to be produced and to be supplied by each supplier to its customers and hence reduces the risk involved in the supply chain. With the use of developed model, managers will be in better position to take decisions under uncertainty.

Use of developed model to reduce the bullwhip effect: The bullwhip effect is phenomenon where order variability goes on increasing as the orders move upstream (from end-user customer to manufacturer) in the supply-chain. Price variability results in demand variability. This effect becomes significant when the cost from fluctuations in production/ordering exceeds the cost of holding inventory. Costs incurred due to bullwhip effect are 1. Setting up and shutting down machines (change of capacities):: In case of bullwhip effect capacitated supply chain is the only agile and dynamic design that allows construction/dismantling of installed machines. Developed model exactly tells when the capacities need to be changed 2. Idling and overtime in the workload or hiring and firing of the workforce::Developed model takes into account the aggregate capacity management option in which optimized results tend to minimize the worker and machine idle time according to the customer demand. Else it goes for other capacity management options like part time temporary workers or adjusting existing workers 3. Excessive inventory at the manufacturer:: In order to maintain an un-interrupted supply the customers till the disruption exists, excess inventory is maintained at the manufacturers end. This way a high service level can be achieved but with a high cost 4. Difficulty in forecasting and scheduling:: Forecasting is capable of achieving the highest possible accuracy in a supply chain. Due to bullwhip effect it becomes difficult to forecast which ultimately leads to incorrect ordering 5. Learning and training new recruits:: As due to bullwhip effect, at times, it is necessary to recruit/fire labors. Whenever new recruits join they need to be trained. Hence, substantial amount of time and money is to be invested in this process. Many of the other consequences of the bull-whip effect cannot be quantified economically. The developed model returns the exact quantity to be produced even in case of abrupt change in customer demand thus minimizing the bullwhip effect impact

Use of developed model for supplier selection: In customer-driven supply chains also called as pull system, customer orders are full-filled immediately after arrival of raw material. The ordered products are delivered to customers by the suppliers/manufacturer immediately on completion. Following are some of the options available for supplier selection 1. Global sourcing from low cost countries 2. Implementing lean operations and manufacturing processes at supplier/

manufacturer end 3. Encourage suppliers to use green technologies for manufacturing 4. Supplier service level along with maintaining high quality. The developed model allows supply chain managers to decide which supplier to select based on customer demand. Also the model facilitates the suppliers to know optimum quantity to be produced hence they get flexibility to select the technology and map their production schedule.

Use of developed model for integrated supply, production and distribution schedule under disruption risks: Aim of supply chain manager is to effectively prepare a production plan and delivery schedule even under disruption risks. Developed model allows both. Following are few other options which the managers can opt for, based on the results obtained from developed model 1. Maintaining high volume of production and inventory so that stock lasts till disruption is recovered and uninterrupted supply is maintained to the customer 2. Designing agile supply chain.

Future Work: In the developed model, we have considered only a single product. The problem under consideration in this thesis is transporting goods from facilities to its customers with an assumption that total quantity produced is shipped. So scheduling of shipments of goods is not considered in this thesis. We have added the emission constraint so as to restrict the amount of carbon emission per facility. An extension to this research could be as follows: multiple products can be considered in the developed model. A math model can be added to find the shortest route and incorporate FLAP and Facility Routing Problem (FRP). More echelons like central distributing, regional distribution center and warehouses could be considered. Inventory management parameter can be incorporated in the model. In emission, carbon trading can be included. By this way multi-objective Integer linear Programming model could be formed. Instead of Simulated Annealing heuristic algorithm, Iterated Local search algorithm can be used for better perturbations in order to explore larger neighborhood solution space

Bibliography

1. Absi, N., Dauzère-Pérès, S., Kedad-Sidhoum, S., Penz, B., & Rapine, C. (2013). Lot sizing with carbon emission constraints. *European Journal of Operational Research, 227*(1), 55-61. doi:http://dx.doi.org/10.1016/j.ejor.2012.11.044

2. Amiri, A. (2006). Designing a distribution network in a supply chain system: Formulation and efficient solution procedure. *European Journal of Operational Research, 171*(2), 567-576. doi:http://dx.doi.org/10.1016/j.ejor.2004.09.018

3. Arabani, A. B., & Farahani, R. Z. (2012). Facility location dynamics: An overview of classifications and applications. *Computers & Industrial Engineering,Vol 62,* pp. 408-420.

4. Averbakh, I., Berman, O., Drezner, Z., & Wesolowsky, G. O. (2007). The uncapacitated facility location problem with demand-dependent setup and service costs and customer-choice allocation. *European Journal of Operational Research, 179*(3), 956-967. doi:http://dx.doi.org/10.1016/j.ejor.2005.11.041

5. Anderson, B. (2012). *The Border and Ontario Economy.* Windsor: University of windsor/Cross-Border Transportation Centre.

6. Ahmed Azab, H.Elmaraghy, P.Nyhuis, J. Pachow-Frauenhofer, M.Schmidt (2013). Mechanics of Change :A frame work to re configure manufacturing system. CIRP Journal of Manufacturing Science and Technology, 6, 110-119.

7. Author Unknown (2013), unpublished note.

8. Bektaş, T., & Laporte, G. (2011). The Pollution-Routing Problem. *Transportation Research Part B: Methodological, 45*(8), 1232-1250. doi:http://dx.doi.org/10.1016/j.trb.2011.02.004

9. Boloori Arabani, A., & Farahani, R. Z. (2012). Facility location dynamics: An overview of classifications and applications. *Computers & Industrial Engineering, 62*(1), 408-420. doi:http://dx.doi.org/10.1016/j.cie.2011.09.018

10. Canel, C., Khumawala, B. M., Law, J., & Loh, A. (2001). An algorithm for the capacitated, multi-commodity multi-period facility location problem. *Computers & Operations Research, 28*(5), 411-427. doi:http://dx.doi.org/10.1016/S0305-0548(99)00126-4

11. Chaabane, A., Ramudhin, A., & Paquet, M. (2012). Design of sustainable supply chains under the emission trading scheme. *International Journal of Production Economics, 135*(1), 37-49. doi:http://dx.doi.org/10.1016/j.ijpe.2010.10.025

12. Correia, I., Melo, T., & Saldanha-da-Gama, F. (2013). Comparing classical performance measures for a multi-period, two-echelon supply chain network design problem with sizing

decisions. *Computers & Industrial Engineering, 64*(1), 366-380. doi:http://dx.doi.org/10.1016/j.cie.2012.11.001

13. C. S. ReVelle, R. W. Swain, Central facilities location, Geographical Analysis2 (1970) 30–42.

14. Canhong Lin, K. C. (2014). Survey of Green Vehicle Routing Problem: Past and future trends. *Expert Systems with Applications*, *Vol 41*,pp. 1118–1138.

15. Canada, S. (2015, May 5). *Statistics Canada*. Retrieved May 31, 2015, from Statistics Canada:
http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=2280069&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid

16. Carlo, P. Spicer. (2007). Integrating Reconfiguration Cost Into the Design of Multi-Period Scalable Reconfigurable Manufacturing Systems. *American Society of Mechanical Engineers*, 202-210.

17. Diabat, A., & Simchi-Levi, D. (2009). *A carbon-capped supply chain network problem.* Paper presented at the 2009 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM 2009), 8-11 Dec. 2009, Piscataway, NJ, USA.

18. Dias, J., Captivo, M. E., & Climaco, J. (2006). Capacitated dynamic location problems with opening, closure and reopening of facilities. *IMA Journal of Management Mathematics, 17*(4), 317-348. doi:10.1093/imaman/dp1003

19. Elhedhli, S., & Merrick, R. (2012). Green supply chain network design to reduce carbon emissions. *Transportation Research Part D: Transport and Environment, 17*(5), 370-379. doi:http://dx.doi.org/10.1016/j.trd.2012.02.002

20. ElMaraghy, A. M. and Deif (2007). capacity scalability scheduling. Investigating optimal *International Journal of Advanced Manufacturing Technology*, 557–562.

21. Elmaraghy, H. A. (2006). Flexible Manufacturing System paradigms. International Journal of Flexible Manufacturing Systems, 17, 261-276.

22. Gebennini, E., Gamberini, R., & Manzini, R. (2009). An integrated production–distribution model for the dynamic location and allocation problem with safety stock optimization. *International Journal of Production Economics, 122*(1), 286-304. doi:http://dx.doi.org/10.1016/j.ijpe.2009.06.027

23. Guastaroba, G., & Speranza, M. G. (2014). A heuristic for ILP problems: The Single Source Capacitated Facility Location Problem. *European Journal of Operational Research, 238*(2), 438-450. doi:http://dx.doi.org/10.1016/j.ejor.2014.04.007

24. G. Pandher and Fazle Baki, (2015). The Critical Disruption in a Cross Border Supply Chain Network.

25. Hinojosa, Y., Puerto, J., & Fernández, F. R. (2000). A multiperiod two-echelon multicommodity capacitated plant location problem. *European Journal of Operational Research, 123*(2), 271-291. doi:http://dx.doi.org/10.1016/S0377-2217(99)00256-8

26. Jin, R. P.-h. (2008). Bi-level simulated annealing algorithm for facility location problem. *International Conference on Information Management, Innovation Management and Industrial Engineering.*

27. Kochenberger, F. G. (2003). *HANDBOOK OF METAHEURISTICS.* Springer.

28. Koren Y. Heisel, U. J. (1999). Reconfigurable Manufacturing Systems. *CIRP Ann*, 527–540.

29. Lee, J.-H., Moon, I.-K., & Park, J.-H. (2010). Multi-level supply chain network design with routing. *International Journal of Production Research, 48*(13), 3957-3976. doi:10.1080/00207540902922851

30. Li, X., Wen, J., & Li, J. (2010). *Research On The Optimization Of Carbon Emissions Of Distribution Centers Location Decision.* Paper presented at the 2010 International Conference on Communications, Circuits and Systems (ICCCAS), 28-30 July 2010, Piscataway, NJ, USA.

31. Lin, C., Choy, K. L., Ho, G. T. S., Chung, S. H., & Lam, H. Y. (2014). Survey of Green Vehicle Routing Problem: Past and future trends. *Expert Systems with Applications, 41*(4, Part 1), 1118-1138. doi:http://dx.doi.org/10.1016/j.eswa.2013.07.107

32. Manzini, R., & Gebennini, E. (2008). Optimization models for the dynamic facility location and allocation problem. *International Journal of Production Research, 46*(8), 2061-2086. doi:10.1080/00207540600847418

33. Melkote, S., & Daskin, M. S. (2001). Capacitated facility location/network design problems. *European Journal of Operational Research, 129*(3), 481-495. doi:http://dx.doi.org/10.1016/S0377-2217(99)00464-6

34. Melo, M. T., Nickel, S., & Saldanha-da-Gama, F. (2009). Facility location and supply chain management – A review. *European Journal of Operational Research, 196*(2), 401-412. doi:http://dx.doi.org/10.1016/j.ejor.2008.05.007

35. M.G.Mehrabi, A. a. (2000). Reconfigurable manufacturing systems: Key to. Journal of Intelligent Manufacturing, 11, 403±419.

36. McKinnon. (2007). *CO2 Emissions from freight transport in the UK. Tech. rep., Prepared for the Climate Change Working Group of the Commission for UK.* Retrieved from <www.isotrak.com/news/press/CO2_emissions_freight_transport.pdf.

37. Minghe. (2012). A tabu search heuristic procedure for the capacitated. *Journal of heuristics*, *vol 21* ,pp.91–118.

38. M.F.Baki (2016), Private communication

39. Ohnishi, H. (2008). *Greenhouse Gas Reduction Strategies in the Transport Sector: Preliminary Report. Tech. rep., OECD/ITF Joint Transport Research Centre.* Retrieved from <http://www.internationaltransportforum.org/Pub/pdf/.

40. Office of the United States Trade. (2015). Retrieved May 31, 2015, from https://ustr.gov/countries-regions/americas/canada

41. Retel Helmrich, M. J., Jans, R., van den Heuvel, W., & Wagelmans, A. P. M. (2015). The economic lot-sizing problem with an emission capacity constraint. *European Journal of Operational Research, 241*(1), 50-62. doi:http://dx.doi.org/10.1016/j.ejor.2014.06.030

42. Spicer and Hector Carlos (2002). Design Principles for machining system configuration. *CIRP*, 275-280.

43.Singh, A. R., Jain, R., & Mishra, P. K. (2013). Capacities-based supply chain network design considering demand uncertainty using two-stage stochastic programming. *International Journal of Advanced Manufacturing Technology, 69*(1-4), 555-562. doi:10.1007/s00170-013-5054-2

44. Nabil Absi, Stephane Dauz`ere-Peres, Saa Kedad-Sidhoum, Bernard Penz,Christophe Rapine, The Single-Item Green Lot-Sizing Problem with Fixed Carbon Emissions,European Journal of Operational Research (2015), doi: 10.1016/j.ejor.2015.07.052

45.Thanh, P. N., Bostel, N., & Péton, O. (2008). A dynamic model for facility location in the design of complex supply chains. *International Journal of Production Economics, 113*(2), 678-693. doi:http://dx.doi.org/10.1016/j.ijpe.2007.10.017

46.Thanh, P. N., Péton, O., & Bostel, N. (2010). A linear relaxation-based heuristic approach for logistics network design. *Computers & Industrial Engineering, 59*(4), 964-975. doi:http://dx.doi.org/10.1016/j.cie.2010.09.007

47.Tognetti, A., Grosse-Ruyken, P. T., & Wagner, S. M. Green supply chain network optimization and the trade-off between environmental and economic objectives. *International Journal of Production Economics*. doi:http://dx.doi.org/10.1016/j.ijpe.2015.05.012

48.Tsiakis, P., & Papageorgiou, L. G. (2008). Optimal production allocation and distribution supply chain networks. *International Journal of Production Economics, 111*(2), 468-483. doi:10.1016/j.ijpe.2007.02.035

49.TAYLOR et al., R. a. (2004). U.S.-Canada Transportation and Logistics: Border Impacts and Costs, Causes, and Possible. *Transportation Journal, Vol. 43, No. 4*, pp. 5-21.

50.Tragantalerngsak et al., J. H. (2000). An exact method for the two-echelon, single-source, capacitated. *European Journal of Operational Research*, *Vol 42*,pp. 473-489.

51. Yoonho Seo, Donghwa Jeong (2008). Facility Location Problem for Reconfigurable Manufacturing System with. *Proceedings of the 2008 IEEE IEEM.* IEEE.

52.Wikipedia. (2015, May Sunday). *Wikipedia*. Retrieved 2015, from Wikipedia.org: http://en.wikipedia.org/wiki/Canada%E2%80%93United_States_Free_Trade_Agreement

53.Wikipedia.org. (2015, July 5). *Wikipedia*. Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Linear_programming

54.www.naftanow.org. (2013, May 6). *NAFTAnow.org*. Retrieved May 31, 2015

55.Wigle and randall (2009) . Welfare costs of border delays: numerical calculations from a Canadian regional trade model/Les couts en bien-etre des retards a la frontiere: analyse numerique a l'aide d'un modele canadien de commerce regional.. (n.d.) >*The Free Library.* (2014).RetrievedSep042015from http://www.thefreelibrary.com/Welfare+costs+of+border+delays%3a+numerical+calculations+from+a...-a0232471038

56. Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design. *Decision Support Systems, 51*(2), 262-269. doi:http://dx.doi.org/10.1016/j.dss.2010.11.020

57. Wikipedia. (2015, October 21). Wikipedia. Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Metaheuristic

58. Wilbert Wilhelm, Xue Han , Chaehwa Lee (2013). Comparison of two formulations for dynamic supply, Computational. *Computers & Operations Research*, 2340-2356.

Appendix

1. Xpress code for Mathematical Modelling

```
model objective

uses "mmxprs"; !gain access to the Xpress-Optimizer solver


parameters


        e=1

        lamda=15

end-parameters


declarations

        !M2: range


        V  = 1..4

        V1 = 1..2 !Canada facility

        V2 = 2..3!US facility

        !V_Vprime = 3..3!{"Newyork","chicago"}

        !V_dash = 1..2! !{"Boston","Austin","Windsor","Burlington"}!All existing facilities

        !V_doubledash = 1..1!all facilities which can be dismantled

        capacities = 1..3 !set of all capacities

        T  = 1..2!all planning horizon

        U  = 1..4!all customers

        U1 = 1..2 !Canada customer
```

U2 = 2..4   !US Customer

S = 1..2!All scenarios

cap:array(capacities) of integer!values of capacities

hti:array(T,U) of integer!demand at customer i in time t

es:array(S) of real

Ps:array(S) of real!probability of scenario

tdash:set of integer

t_dash:set of integer

H_hatj:array (V)of integer!capacities of existing facilities

!all cost parameters

a_tkj: array(T,capacities,V) of real!cost of setting facility at j of capacity k at time t

a_bar_tkj:array(T,capacities,V) of integer!cost of removing facilities

!transportation cost

de1_tji:array(T,V,U) of integer

!de2_tji:array(T,Vcombine,U) of integer

!Decision VAriables

y_tkj:array (T,capacities,V) of mpvar !binary variable

!y_dash_j:array (V_Vprime) of mpvar !binary variable

y_hat_tkj:array(T,capacities,V) of mpvar!binary variable for decision

Z_tsji:array(T,S,V,U) of mpvar

end-declarations

initializations from "try13.txt"

Ps es cap H_hatj a_tkj a_bar_tkj hti de1_tji

end-initializations

objective:=

(sum(t in T,k in capacities,j in V)(a_tkj(t,k,j)* y_tkj(t,k,j)))+(sum(t in T,k in capacities,j in V)(a_bar_tkj(t,k,j)* (y_ hat_tkj(t,k,j))))+(sum(t in T,s in S,j in V1,i in U1)(Z_tsji(t,s,j,i)*de1_tji(t,j,i)))+(sum(t in T,s in S,j in V2,i in U2)(Z_tsji(t,s,j,i)*de1_tji(t,j,i)))+(sum(t in T,s in S,j in V1 ,i in U2)(Z_tsji(t,s,j,i)*de1_tji(t,j,i)*(1+es(s))))+(sum(t in T,s in S,j in V2 ,i in U1)(Z_tsji(t,s,j,i)*de1_tji(t,j,i)*(1+es(s))))+sum(t in T,s in S,j in V,i in U)Z_tsji(t,s,j,i)*e*lamda

```
!Contraints 1


        forall(t in T )do

                forall(s in S) do

                        forall(i in U) do

                                con6(t,s,i):=sum(j in V)Z_tsji(t,s,j,i)>= hti(t,i)* Ps(s)

                        end-do

                end-do

        end-do
!constraint 2



        forall(t in T)do

        !tdash += {t}

        forall(j in V,t1 in 1..t)do

                !forall (t1 in tdash) do


sum(i in U,s in S)Z_tsji(t,s,j,i)<=H_hatj(j) +sum(k in capacities)cap(k)*y_tkj(t1,k,j)-sum(k in
capacities)cap(k)*y_hat_tkj(t1,k,j)

                end-do

        end-do
```

!constraint 3

```
forall(t in T,j in V)do

        sum(i in U,s in S)Z_tsji(t,s,j,i)*e <= 25000

    end-do
```

!constraints for decision variables

```
forall(t in T)do
        forall (s in S)do
                forall (j in V)do
                        forall (i in U)do
                        Z_tsji(t,s,j,i) is_integer
                        end-do
                end-do
        end-do
end-do


forall(t in T) do
```

```
          forall (k in capacities)do

                    forall (j in V)do

                              y_tkj(t,k,j) is_binary

                    end-do

          end-do

end-do


forall(t in T) do

          forall (j in V)do

                              forall (k in capacities)do

                                        y_hat_tkj(t,k,j) is_binary

                              end-do

          end-do

end-do
```

!objective function

minimize(objective)

!output

writeln("value of the objective is=",getobjval)

```
forall(t in T)do

        forall (s in S)do

                forall (j in V)do

                        forall (i in U)do

                        !        if (Z_tsji(t,s,j,i)<>0)then

                                        writeln("Z_tsji(",t,",",s,",",j,",",i,")=
",getsol(Z_tsji(t,s,j,i)))

                                !end-if

                        end-do

                end-do

        end-do

end-do




end-model
```

2. Flowcharts

1.   Swap operator
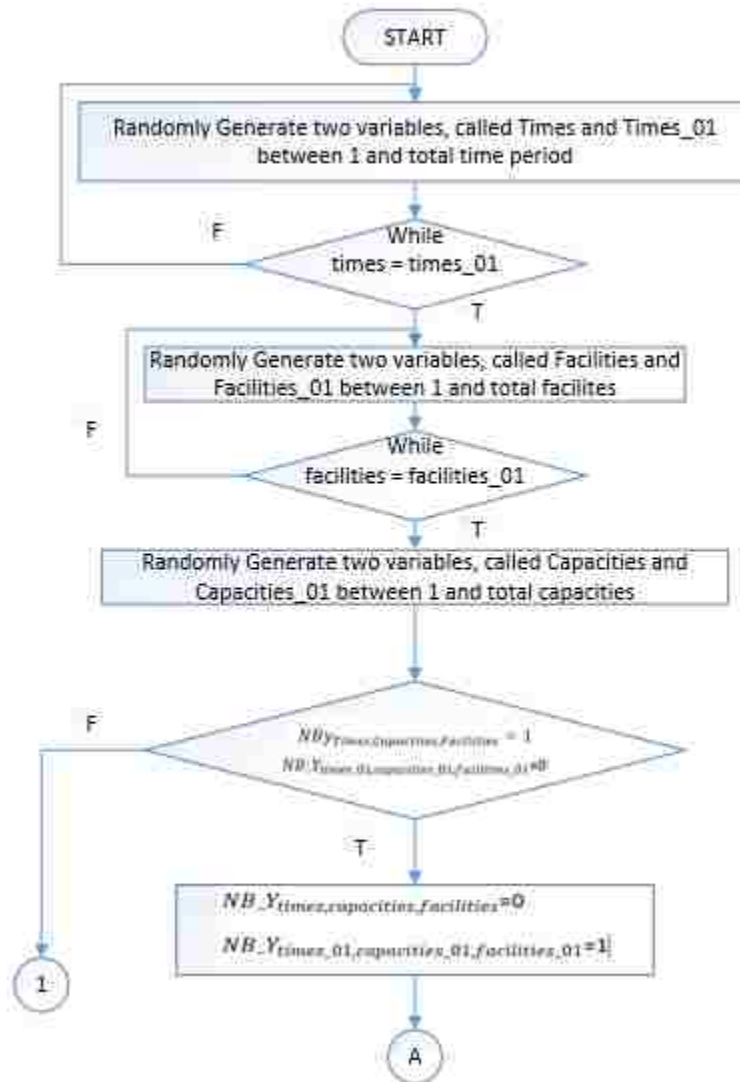
Figure 12 Swap operator flow chart
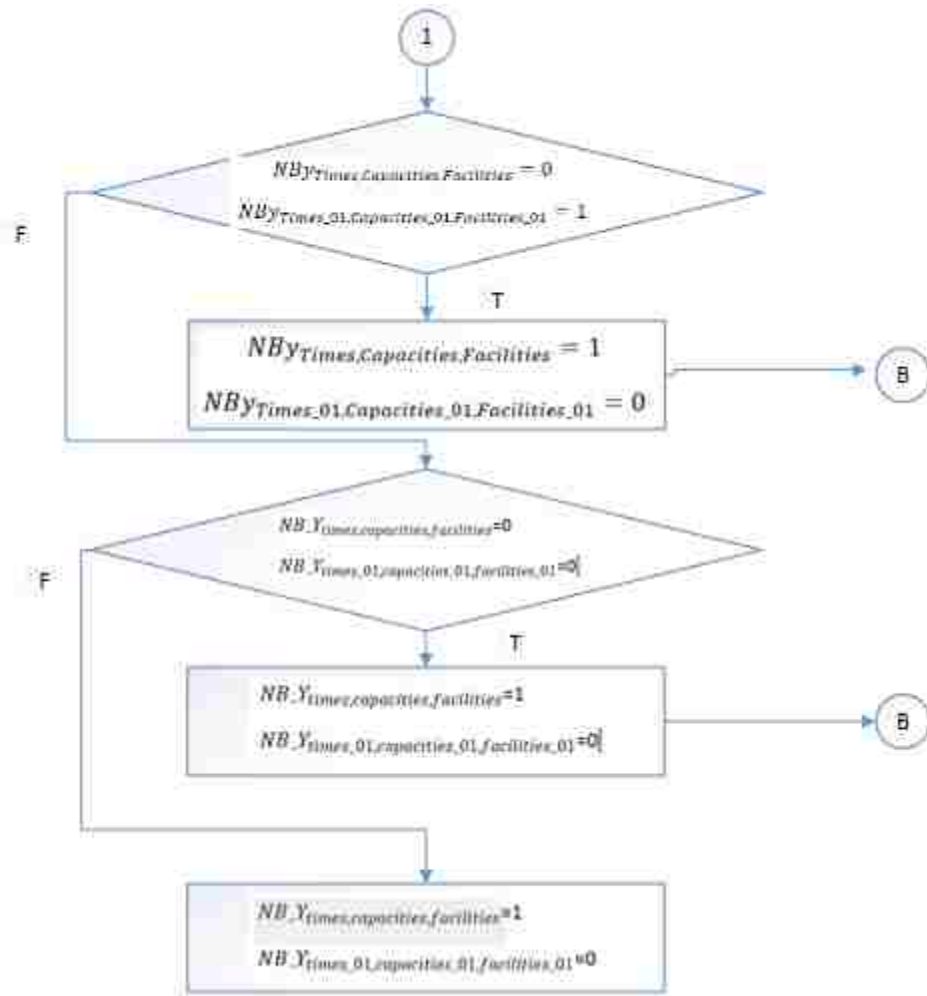
Figure 13 Swap operator flow chart continued
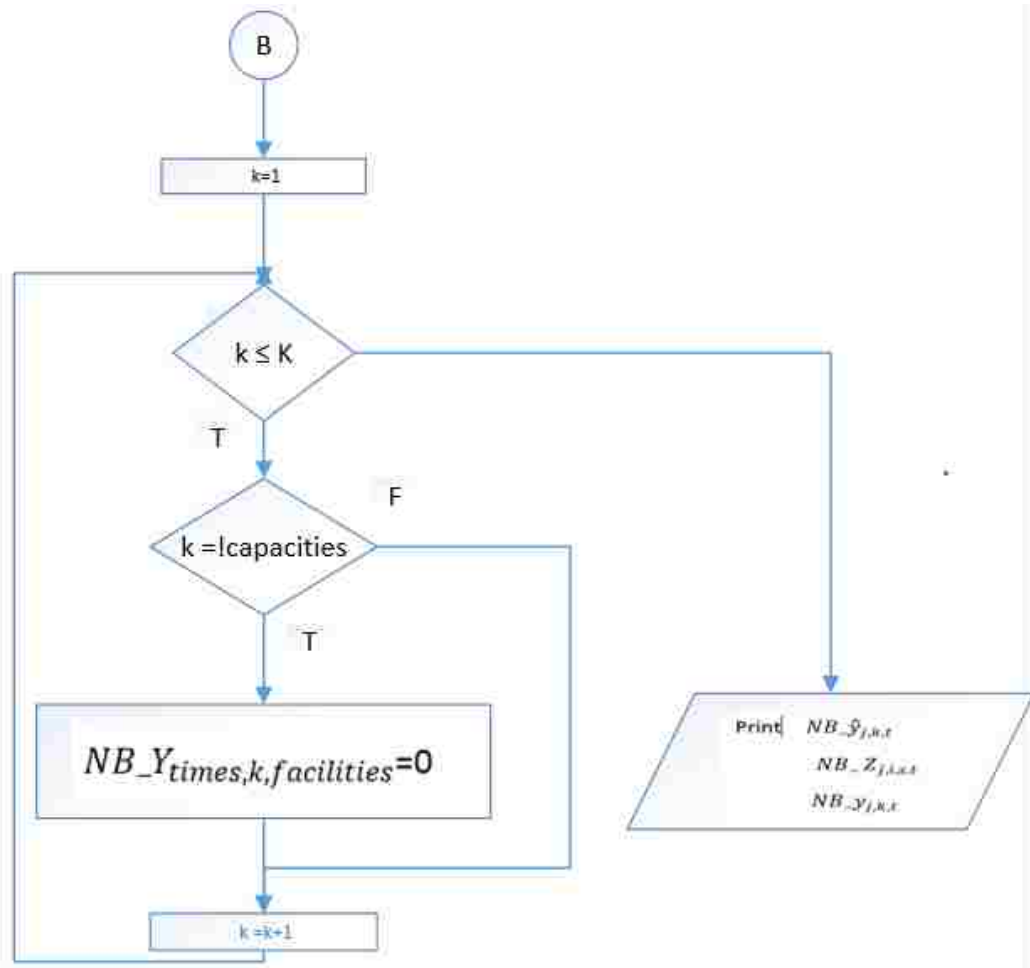
Figure 14 Swap operator flow chart continued
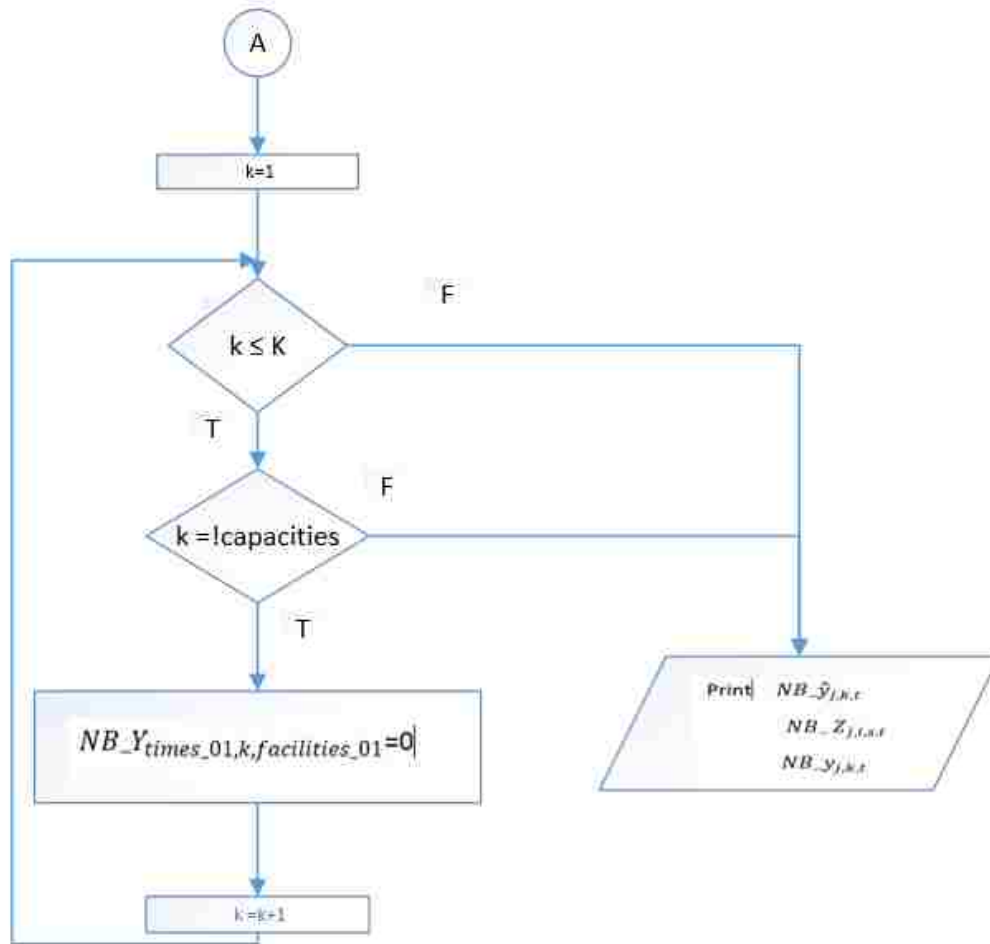
Figure 15 Swap operator flow chart continued

2. Constraint 5
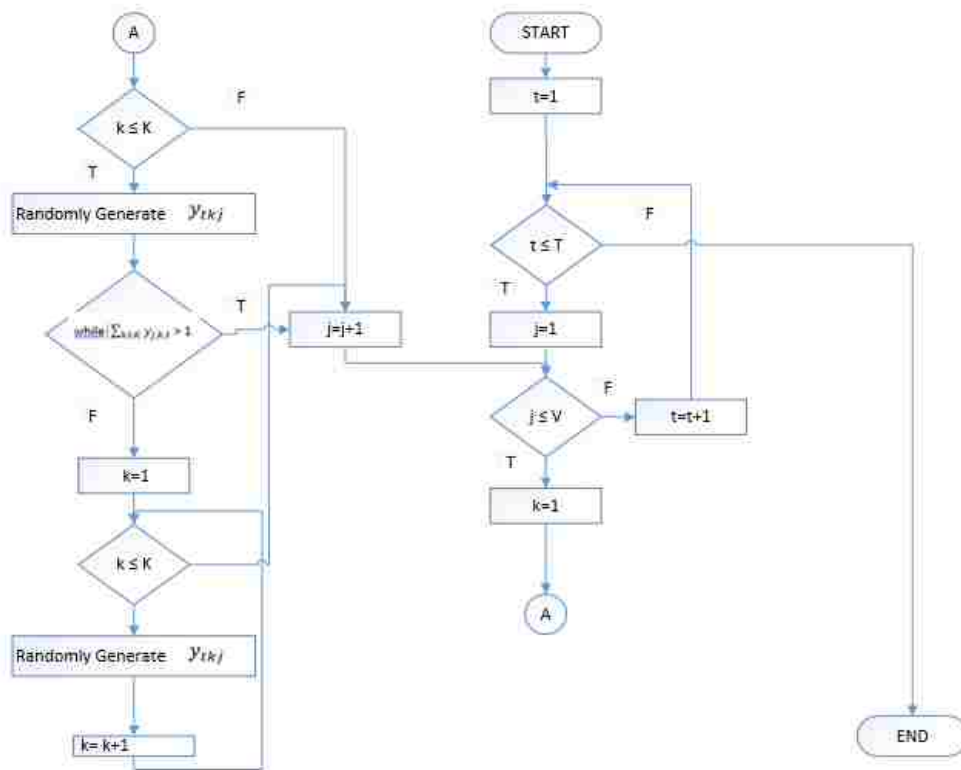
Figure 16 Constraint 5 flow chart

3.	Decision $y_{j,k,t}$ variable generation
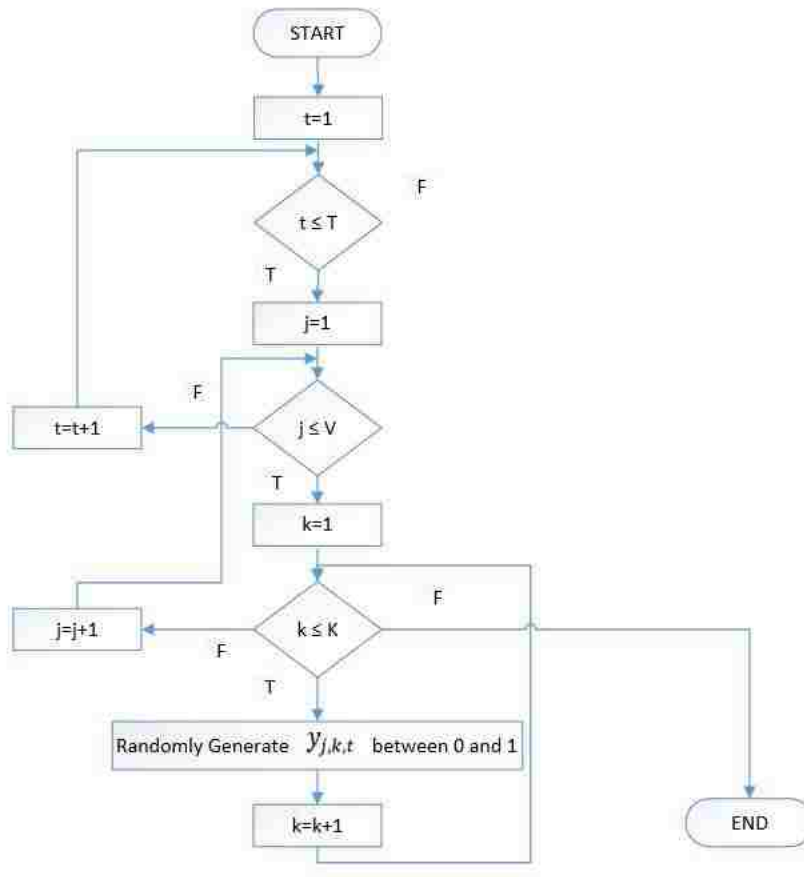
Figure 17 Decision variable generation flow chart

4. Demand Repair Function
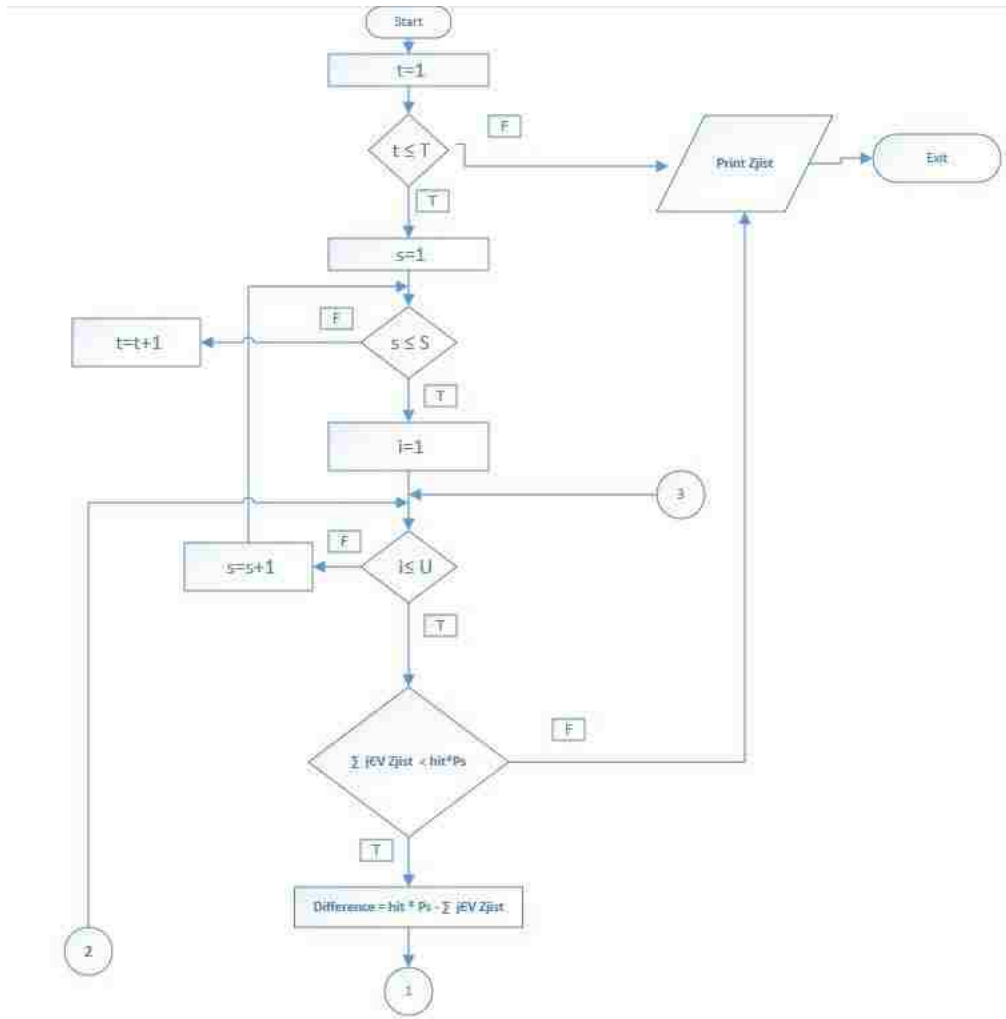
Figure 18 Demand Repair Function flow chart
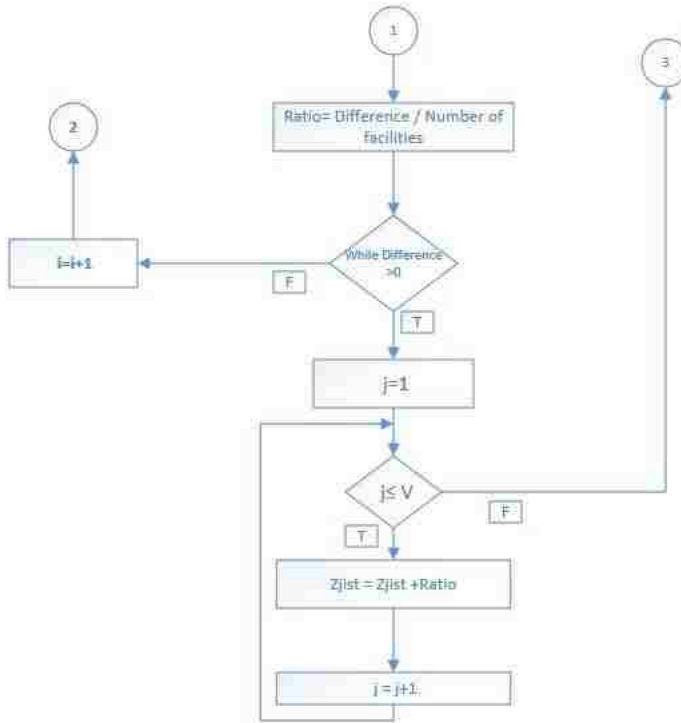
Figure 19 Demand Repair Function flow chart continued

5.   Emission Repair Function
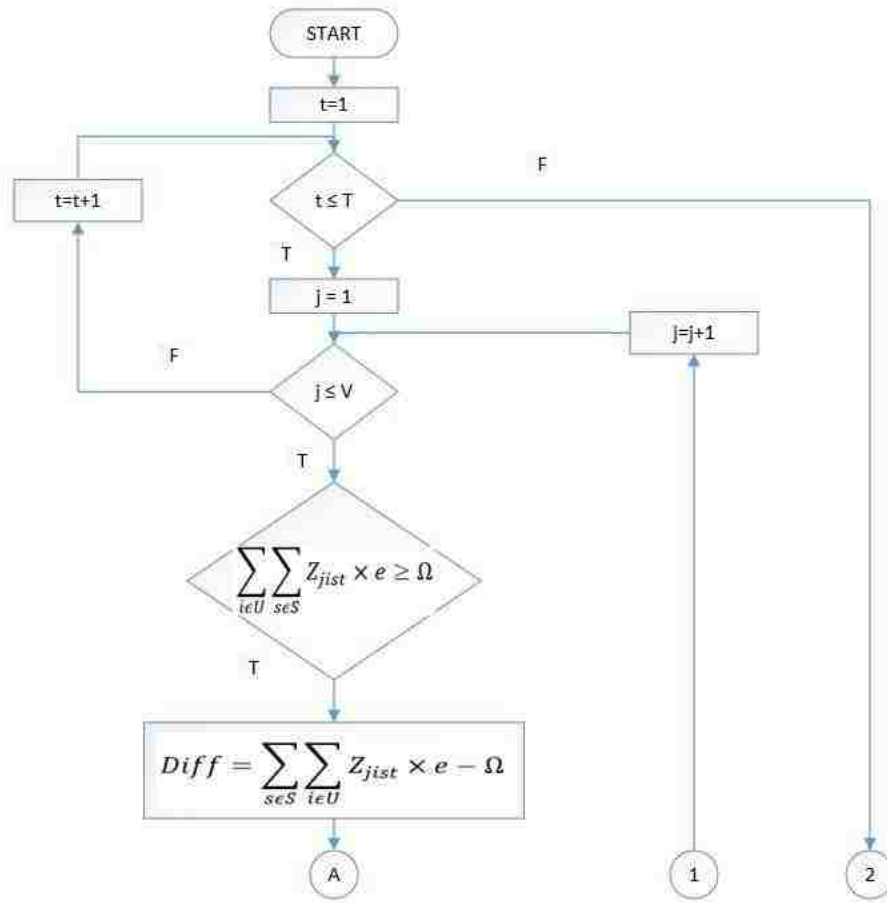
Figure 20 emission repair function flow chart

$$ratio = {Diff}\big/{(No\ of\ Customer\ \times No\ of\ Scenarios)}$$

While $Diff > 0$

i = 1

i ≤ U

s = 1

s = s+1

s ≤ S

$Z_{jist} \geq ratio$

$$Z_{jist} = Ceil(Z_{jist} - ratio)$$

Print Z_{jist}

END
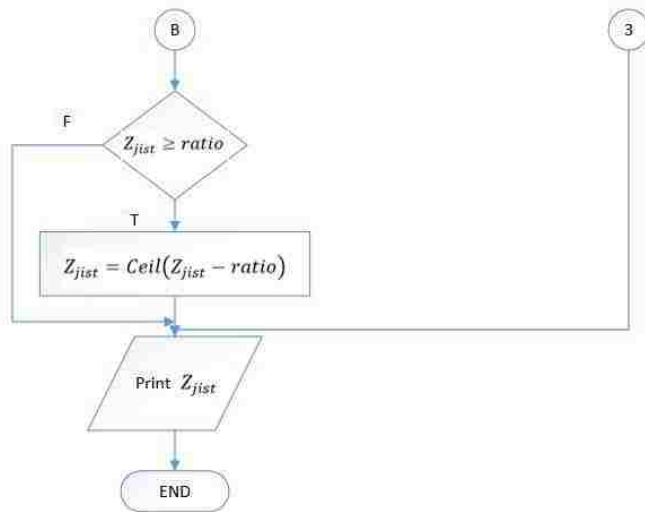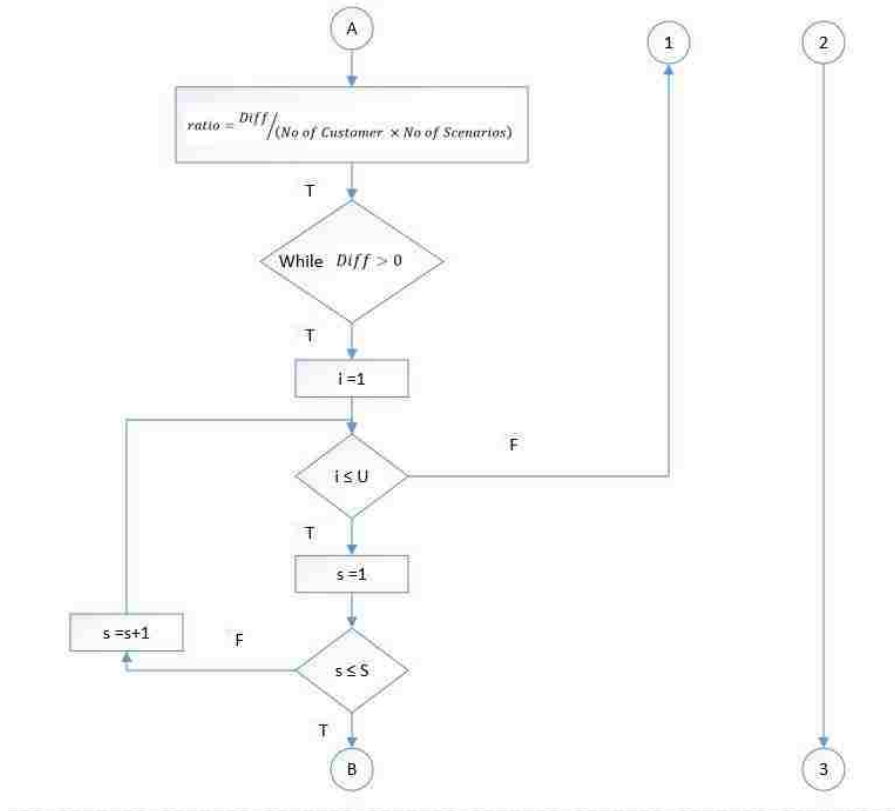
Figure 21 emission repair function flow chart

99

6.   Excess Repair Function
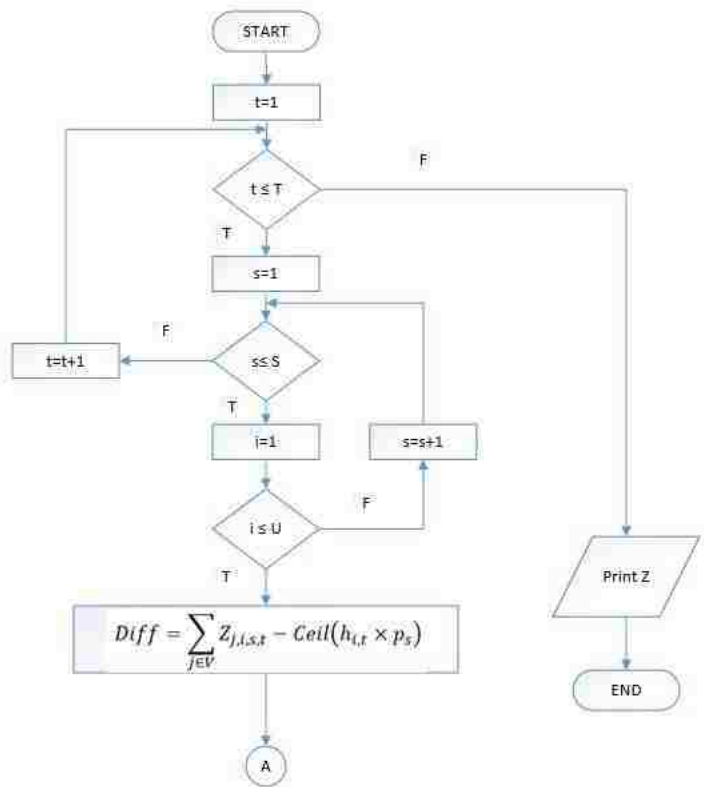
Figure 22 Excess repair function flow chart
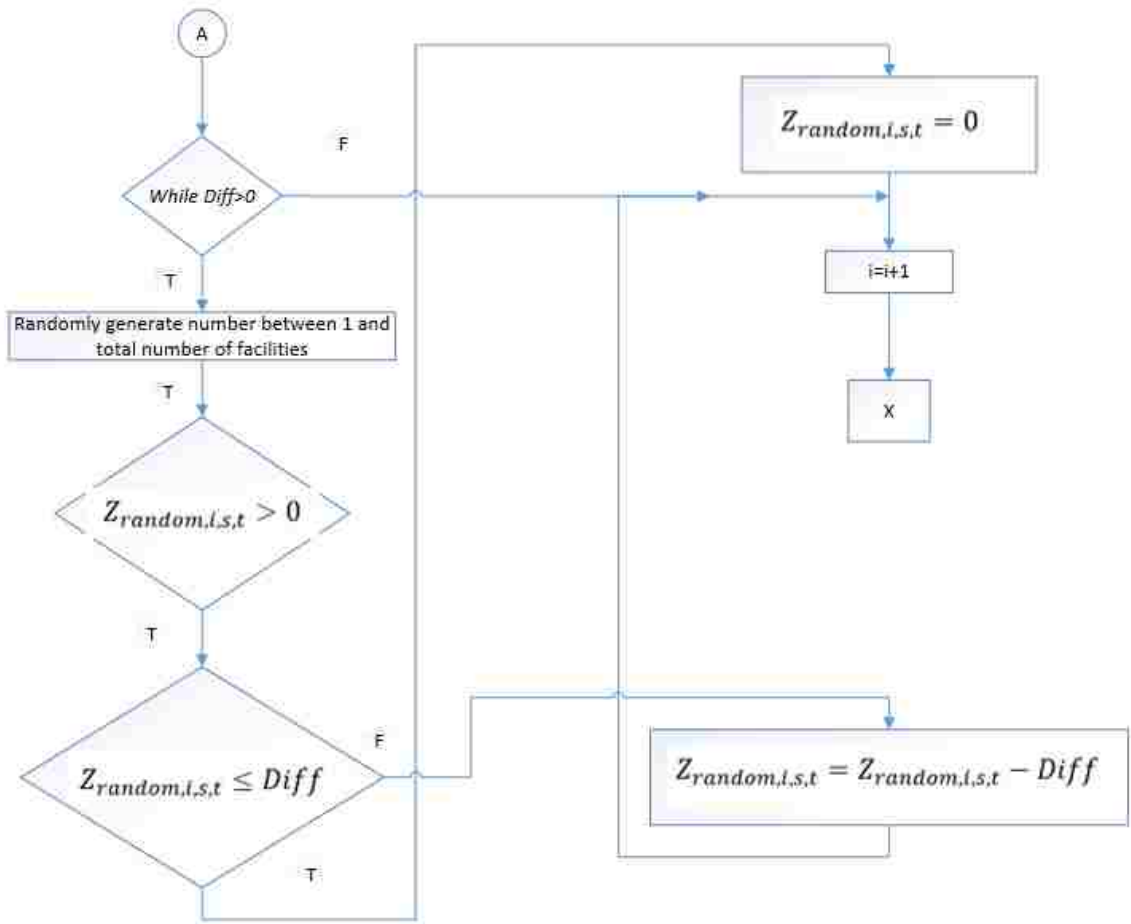
Figure 23 Excess repair function flow chart

7. Constraint 4
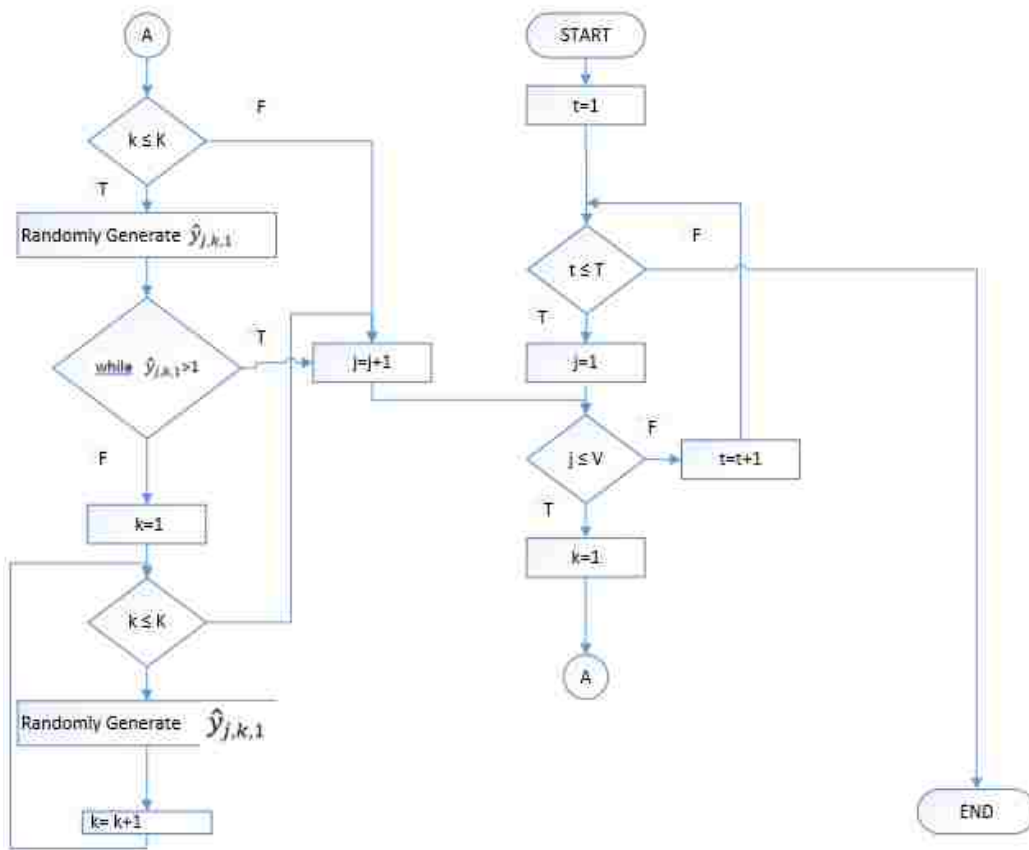
Figure 24 Constraint 4 flow chart

8. Merge operator
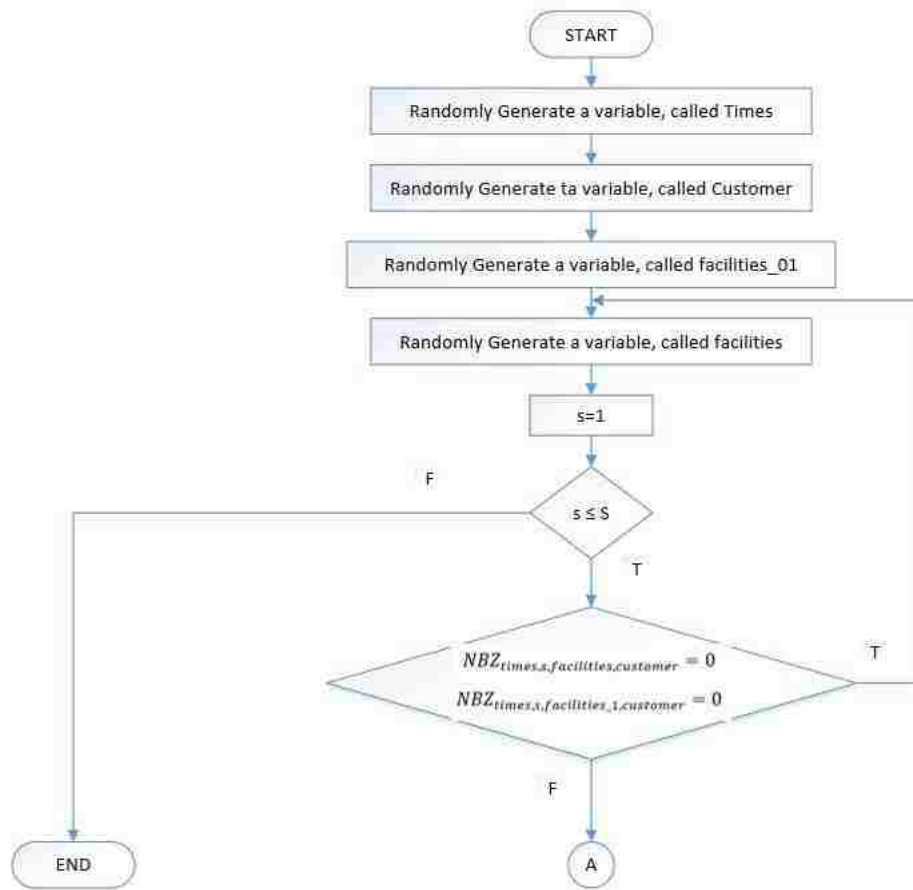
Figure 25 Merge operator flow chart
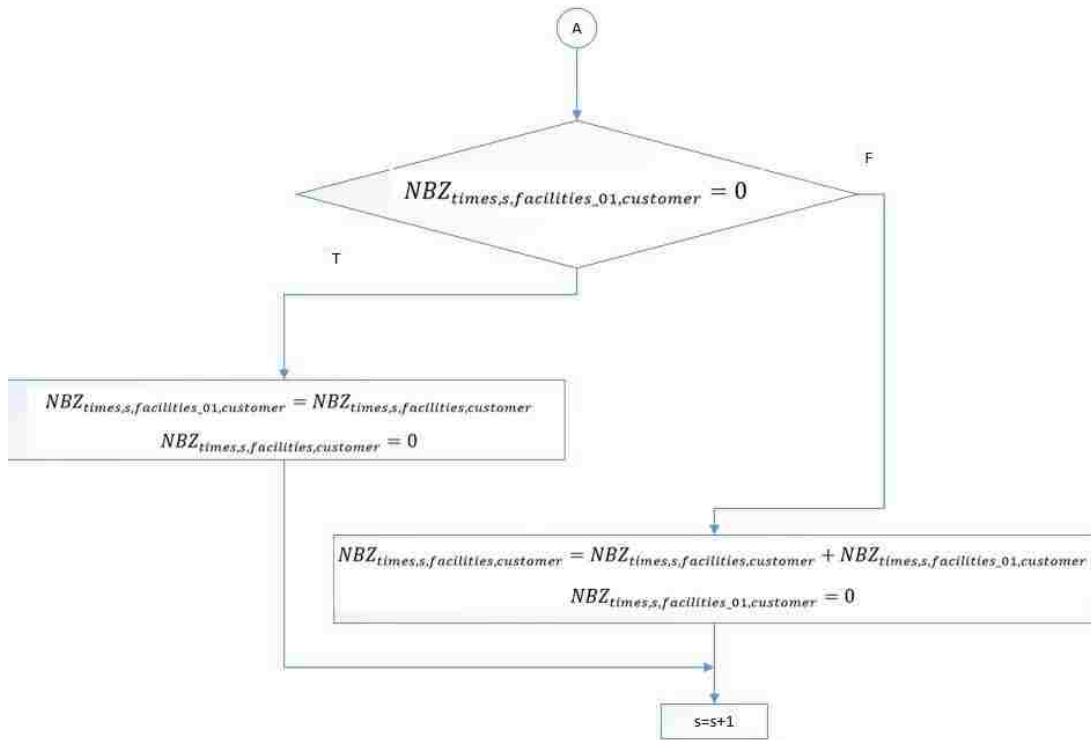
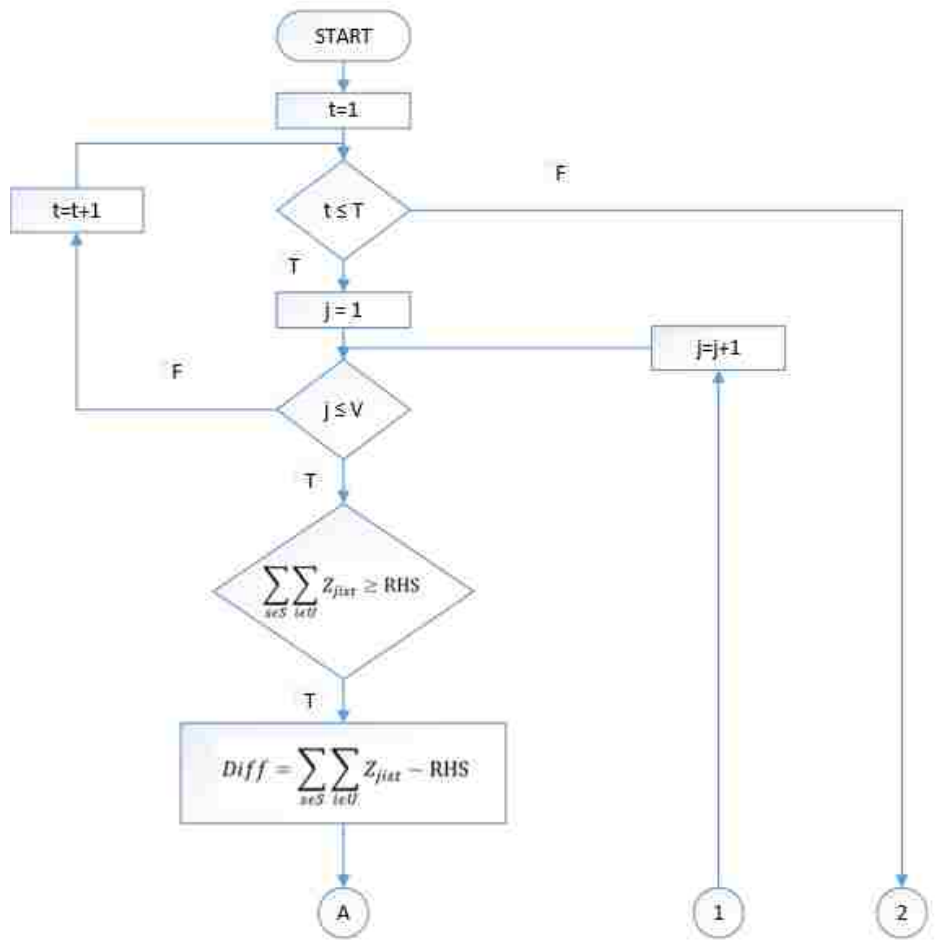*Figure 26 Merge operator flow chart continued*

9. Production Repair Function

Figure 27 Production repair function flow chart
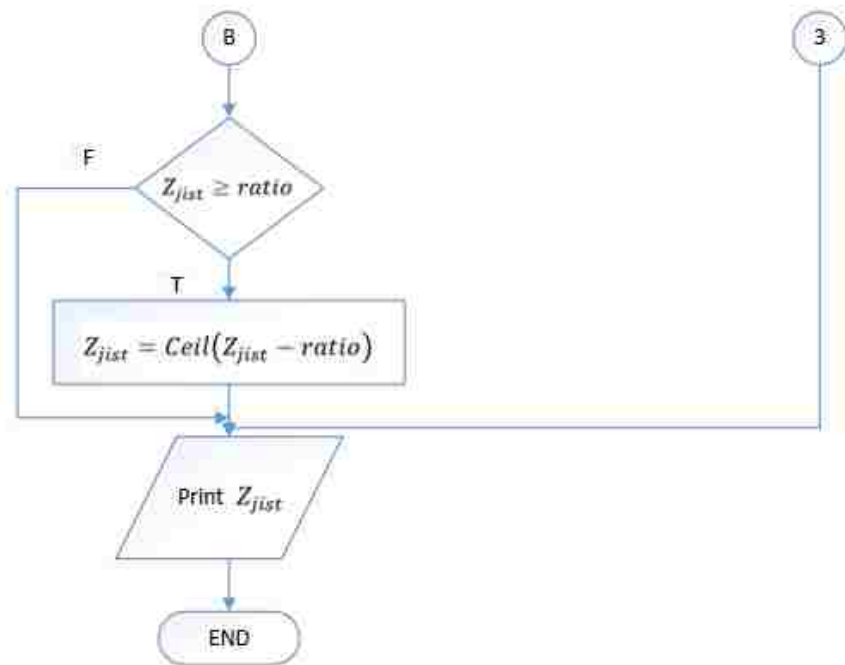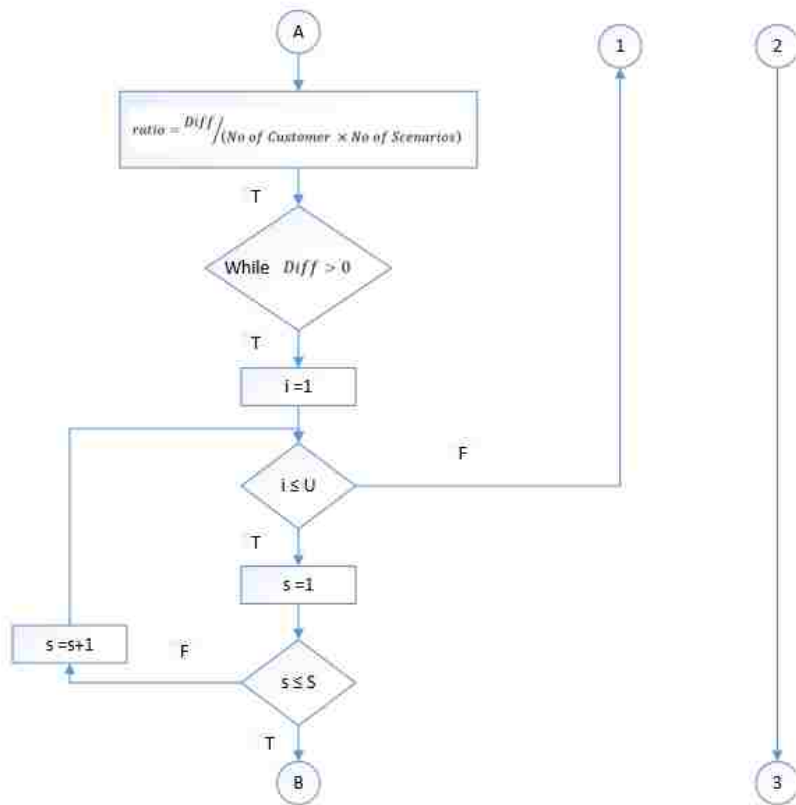
A

$$ratio = \frac{Diff}{(No\ of\ Customer\ \times No\ of\ Scenarios)}$$

T

While $Diff > 0$

T

i = 1

i ≤ U

F

1

2

T

s = 1

s = s+1

F

s ≤ S

T

B

3

B

3

F

$Z_{jist} \geq ratio$

T

$$Z_{jist} = Ceil(Z_{jist} - ratio)$$

Print Z_{jist}

END

10. RHS Repair function

$$RHS = \widehat{H}_j + \sum_{t \leq t} \sum_{k \in K} y_{jkt} \times H_k - \sum_{t \leq t} \sum_{k \in K} \widehat{y_{jkt}} \times H_k$$
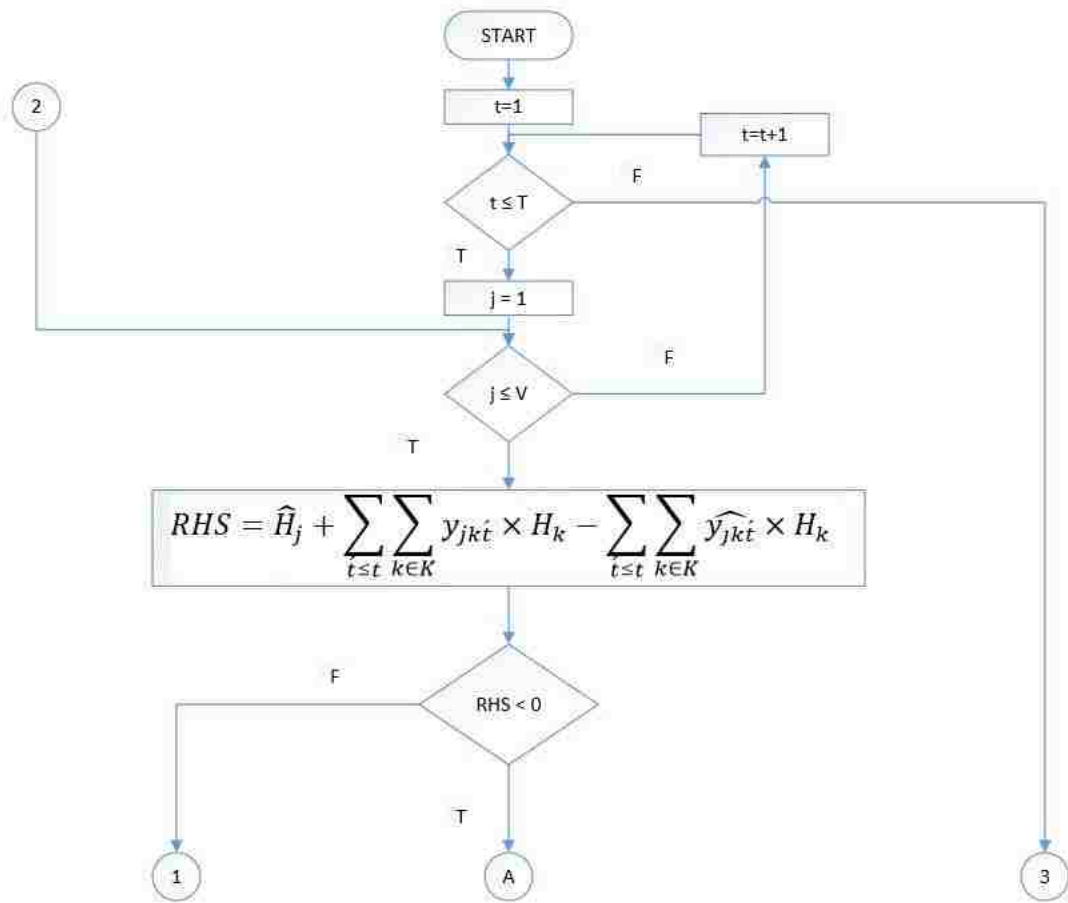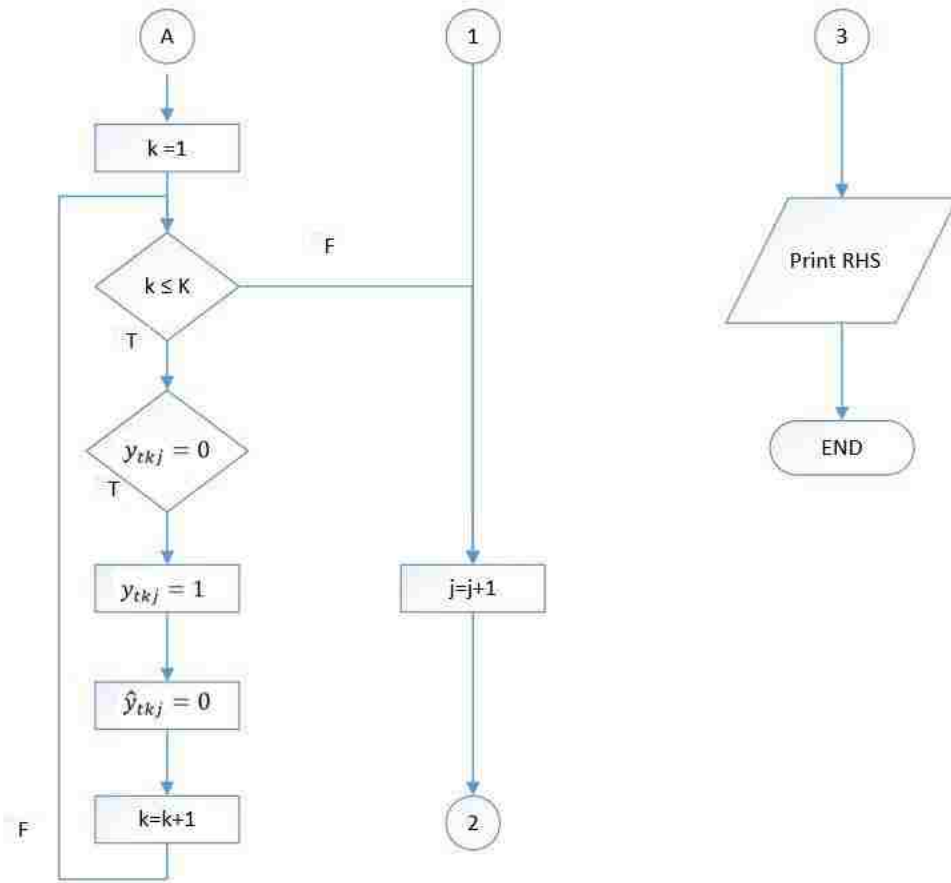
Figure 28 RHS repair function flow chart

Figure 29 RHS repair function flow chart

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