A MIXED INTEGER PROGRAMMING MODEL FOR A MULTI-CHANNEL MULTI-PERIOD CLOSED-LOOP GREEN SUPPLY CHAIN

ABSTRACT

Currently in most of the literature in supply chain management either considers only a part of the supply chain or the total supply chain in some simplified manner or either the green objective, closed loop, multi period framework, multi-channel supply chain networks separately or some of them at a time, but this paper holistically considers the complete supply chain with all of them. This project Multi-Channel Multi-Period Closed Loop Green Supply Chain Network considers most of the strategic and tactical decisions faced by a real-world supply chain consisting of all the five stages, namely, suppliers, manufacturing plants, warehouses, retailers and recycling centers. The modeling decisions will include the selection of the entity that will fulfill the demands of the customer to reduce the total cost incurred to the customer and the supplier selection process integrated with the production amounts, inventory levels, stock-outs and shipment quantities. The project proposes an integrated mathematical programming model for supply chain management. The aim of the project is to minimize the total cost incurred to the customer, total cost incurred in running the supply chain and minimize the total pollution emissions from all the transportations of the products between the different stages of the supply chain. Moreover the various outputs of quantitates, costs and emissions of the 3 different scenarios and 2 risk/sensitivity analysis cases are considered and compared Mixed integer linear program is used to configure the model.

Keywords: Multi-Channel, Multi-Period, Green Supply Chain, Mixed Integer linear programming.

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CHAPTER 1 INTRODUCTION

A supply chain consists of organizations, people, activities, information and resources which help in moving a product or service from supplier to customer. A supply chain activity transforms natural resources, raw materials, and components into a finished product and then delivers it to a customer. In more complex supply chain systems, if used products have a residual value which is recyclable, they may enter the supply chain at any point. The key elements of Supply Chain and its management are the upstream groups, the downstream groups and the collaboration of all the organizations involved, along with the internal functions of the organization. The upstream groups consists of an organization's functions, processes and network of suppliers while the downstream group consists of the distribution channels, processes and functions through which the product passes to the end customer.

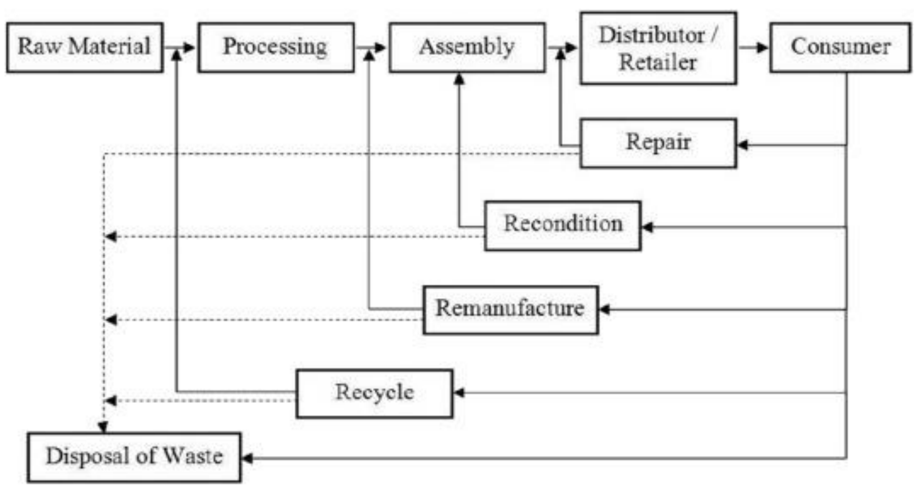

Figure 1 Closed Loop Supply Chain

1.1 TYPES OF SUPPLY CHAIN

Forward Supply Chain- A forward supply chain consists of a network of facilities and distribution options that performs different operations on materials, transforms these materials into intermediate and finished products, and the distributes these finished products to customers. Supply chains exist in both service and manufacturing organizations, although the complexity of the chain may vary according to the type of industry. Optimizing the supply chain networks in the real world business environment is a very difficult task because the supply chain involves hundreds of facilities and thousands of products. The supply chain leader, usually referred to the manufacturer in the supply chain, has to deal with uncertainties in supply and demand with conflicting objectives, analyze and understand where and when the tradeoffs might occur along the different elements of the supply chain.

Reverse Supply Chain- A reverse supply chain focuses on the backward flow of materials from customer to supplier. The product is either reused or disposed. The main aim is in maximizing the value from the returned item or minimizing the total reverse logistics cost. Reverse distribution can take place through the original forward channel, through a separate reverse channel, or through combinations of both forward and reverse channel.

Closed Loop Supply Chain- Closed loop supply chain (CLSC) consists of both the forward supply chain and reverse supply chain. The importance of economic development without affecting the environment, and strict regulations on the wastage caused right from the inception of a product, through its life period and after it has increased the growing attention on closed loop supply chain. The forward supply chain essentially involves the movement of goods/products from the upstream suppliers to the downstream customers. The reverse supply chain involves the movement of used/unsold products from the customer to the upstream supply chain for possible recycling and reuses. It has been found that an integration of forward supply chain and reverse supply chain can lower the overall costs and at the same time adhere to governmental and environmental regulations. Hence, it is important to model and analyze closed loop supply chains as a system in total, without splitting it into distinct parts of forward and reverse supply chains.

Green Supply Chain- The realization of the need for environmental protection and that by wasting fewer materials by reusing and remanufacturing can lead to financial gains has made manufactures move towards a green supply chain management. In spite of conventional supply chain management, green supply chain management demands recycling and a closed loop logistic is required for material flow within supply chains.

1.2 SUPPLY CHAIN INTEGRATION

The need for the integration of information technology and process is required for the success of a business in the global world. Many manufactures and service providers are collaborating with their primary suppliers to upgrade the traditional material management functions and adapt it into part of their corporate strategy. They have adopted an integrated strategic approach to SCM. Although many efforts have failed; it still has become a significant tool for firms striving to advantage. Supply chain integration enables members of the supply chain to function as a unified logistics quantity wherein all the supply chain entities and operations including purchasing, manufacturing and logistics function can be more efficiently and effectively managed.

1.3 SUPPLY CHAIN MODELLING

A typical supply chain model consists of multiple stages such as suppliers, manufacturers, distribution centers, warehouses, retailers etc. They can be classified into two broad categories (i) Production Planning and Inventory Control (ii) Distribution and Logistics. These processes interact with each other to produce an integrated supply chain. Inventory policies affect the cost and responsiveness of the supply chain. No, mathematical model can capture all aspects of the supply chain process. To compromise the dilemma between model complexity and reality, a model should be designed in such a way that it is has all key real world dimensions, yet not too complicated to solve.

CHAPTER 2 LITERATURE REVIEW

2.1 INTEGRATED SUPPLY CHAIN MODELLING

Anil Jindal et.al, (2015) have proposed a network design for the optimization of a multi-time, multi-product, multi-echelon closed-loop supply chain in an uncertain environment. The uncertainty considered includes ill-known parameters which are handled with fuzzy numbers. **Kiran Garg et al., (2015)** attempted to deal with environmental issues in a Closed Loop Supply Chain network. They formulated a bi-objective integer nonlinear programming problem.

The result of their model suggests that, an enterprise can project a ecofriendly image of their product which significantly reduces their usage of transportation in both directions, and results in an increase in their demand. **Niels A.H. Agatz et.al, (2008)** address the supply chain network issues related to internet in the multi-channel environment and provide a systematic overview of the managerial planning tasks and their corresponding quantitative models. **A. Ahmadi Yazdi , M. Honarvar (2014)** proposed a new model for designing the integrated forward/reverse logistics based on pricing policy for direct and indirect sales channel.

A deterministic mixed integer linear programming model is developed for an integrated logistics network design. A mixed integer linear programming model using scenario-based stochastic approach is developed.

Yanhui Li et.al, (2013) formulated a location-inventory-routing problem model with emphasis on the problem in e-commerce logistics system, with no quality defects returns and developed an effective hybrid genetic simulated annealing algorithm (HGSAA) to resolve this NP-hard problem.

They show that HGSAA outperforms GA on computing time, optimal solution, and computing stability. **Saman Hassanzadeh Amin and Guoqing Zhang (2014)** developed a network that includes multiple products, plants, demand markets, recovery technologies, and collection centers. The model can determine number and locations of open facilities, and flows of products in the network. Apart from minimizing the total cost, a multi-objective model considering minimization of defect rates and time of operations in collection centers is developed. **Juan Yu et.al, (2015)** studied the dual-channel (the traditional channel and E-commerce channel) supply chain network design (SCND) under information uncertainty. The model tries to solve the problems in integration network design and minimize the supply chain operation cost and the maximize the degree of satisfaction between the logistics demand and the supply chain (SC) nodes simultaneously.

T Biswas & Susmita Samanta (2016) proposed a mixed integer linear programming model to tackle the logistics and supply chain network design of a multi-commodity, multi-stage, and multi-period distribution and transportation system problem while simultaneously minimizing the operating, transportation and the handling costs through all the tiers of a supply chain network using genetic algorithm based method . **Xiaohua Ha et.al, (2016)** studied the collection channel and the production decisions in a closed-loop supply chain (CLSC) with one retailer and one dominant manufacturer from the point of view of both the firm profit and system robustness.

The direct channel is more robust while facing disruptions and they generate more profits for manufacturers when there is a large positive disruption and the revenue-sharing contracts are effective in coordination. **Francesco Costantino et.al, (2014)** proposed a multi-criteria decision making methodology for selecting and evaluating the logistics distribution networks in a customized environment, basing on an analytic network process (ANP). As a first step of the design process, this method helps the decision maker in the selection of the best configuration of logistics distribution. **Kanchan Das and Nageswara Rao Posinasetti (2015)** developed a model that includes a modular product design for facilitating faster manufacturing, remanufacturing, refurbishing, disassembly, and repairing using new subassemblies. The model plans a sustainable module formation as well as a production method for components and products, and transportation and distribution routes for obtaining an optimum business performance and to considers the environmental concerns for the harmful emissions and the spent energy. **Vaidyanathan Jayaraman and Hasan Pirkul (1999)** have proposed a distribution strategy, considering the product mix at each plant as well as the shipments of raw material from vendors to the manufacturing plants and the distribution of finished products from plants to the different customer zones via a set of warehouses.

A mixed integer programming formulation and a heuristic solution procedure that utilizes the solution generated from a Lagrangian relaxation of the problem is used and found to be efficient and effective. **Vaidyanathan Jayaraman and Anthony Ross (2001)** describe the PLOT (Production, Logistics, Outbound, and Transportation) design system. They systematically evaluated the computational performance for different problem scenarios.by extending the breadth of applications and studying a new combinatorial problem incorporating a cross-docking in a supply chain environment and **Kaijun Liu et.al, (2010)** presented a location model in a two –echelon logistics system .This model assigns the online demands for the capacitated regional warehouses currently serving the in-store demands in a multi-channel supply chain and explicitly considers the trade-off between risk pooling effect and transportation cost.

2.2 GREEN SUPPLY CHAIN MANAGEMENT

ImenNouira et al showed that supply chain optimization models should identify the correlation between the environmental performance of a product (in terms of carbon emissions), customer demand, and supply chain decisions. The author considered the emissions associated with the transportation from suppliers to production facilities) the production process, and the transportation from production facilities to customers. The main decisions used in the model are the selection of suppliers, the location of production facilities, the selection of production technologies, and the selection of transportation modes.

"Eco-efficient supply chain networks: development of a design framework and application to a real case study". **Claudia Colicchia et al** showed that a network optimizing the costs may lead to beneficial effects for the environment and that a minor increase in distribution costs can be offset by a major improvement in environmental performance. The paper addressed the topic of supply chain network design for eco-efficiency. The author proposed supply chain network design framework to develop an eco-efficient model, one that can simultaneously take into account both economic and environmental performance.

2.3 Objective

In this project, mixed integer linear programming model is proposed to configure a multi –objective CLSC network including multiple plants, products, recycling centers. New products manufactured are sent from plants to demand markets. This project is a Multi-Channel Multi-Period Closed Loop Green Supply Chain Management model which considers most of the strategic and tactical decisions faced by a real-world supply chain consisting of all the five stages, namely, suppliers, manufacturing plants, warehouses, retailers and recycling centers. The modeling includes the selection of the entity that will fulfill the demand of the customer to reduce the total cost incurred to the customer and the supplier selection process integrated with the production amounts, inventory levels, stock-outs and shipment quantities. Some of the products are returned for recycling. Green supply chain is incorporated by reducing the pollution emission. Various outputs of the supply chain quantities, costs and emissions of the 3 different scenarios and the 2 risk/sensitivity analysis cases are to be considered and compared. The model is implemented for a data set using the software CPLEX.

2.4 Research Gap

Based on the literature review above, it is evident that there has been a lot of research done in the areas of supplier selection and supply chain modeling and a few papers combining both, using nontraditional methods such as AHP. However, there is no work that integrates both the supplier selection problem along with the inventory, production and transportation problems across the various stages of the supply chain as a single mathematical model. Currently most of the literature in supply chain management either considers only a part of the supply chain or the total supply chain in some simplified manner or either the green objective, closed loop, multi period framework, multi-channel supply chain networks separately or some of them at a time, but this paper holistically considers the complete supply chain with all of them. Also, comparisons of various cases particularly the one with the traditional supply chain and the multi-channel model has not been previously considered before in depth. Moreover there is no research that has modeled supply chain models over multiple periods for a multi-channel model. This paper unlike previous research works has not assumed the customer demand but has calculated the cheaper and the better options available and then optimized the supply chain for the set of customer demand. This thesis is a first step in that direction.

CHAPTER 3 METHODOLOGY

3.1 PROBLEM DESCRIPTION

A multi-channel closed loop green supply chain has been considered which includes suppliers, manufacturers, warehouse, retailers, recycling centers and three types of customer demands.

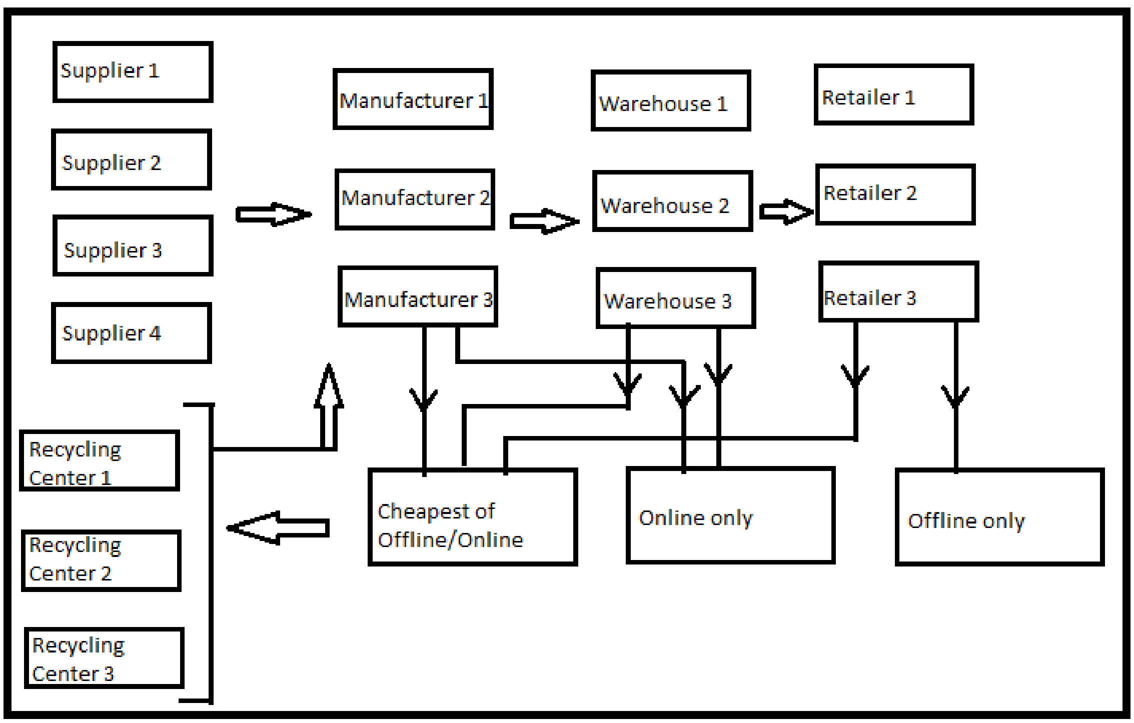

Figure.3 Schematic representation of the Supply Chain Problem

It basically is a closed loop supply chain where the used products by the customer is sent to the recycling center of which 50% is sent to the manufacturer to complete the loop with a repair cost for the recycled products. 3 suppliers, 3 manufacturers, 3 warehouses, 3 retailers, 3 recycling centers and 5 customers each of the 3 demand types are considered.

To realize the multi-channel, four types of customers are being considered. By means of this, a strong link between retailers and online partner is realized. The various customer demands are:

1. Online order with direct home delivery from either warehouse or manufacturer
2. Offline customers getting products instantly from the retailer
3. Customers who choose the cheapest channel of offline/online

Green supply chain is incorporated by reducing the pollution emission. The entire supply chain is solved over multiple time periods (10 time periods). It is assumed that it takes 1 time period to transport the product and the raw materials between the consecutive echelons. Inventory is present at the warehouse, retailer and the recycling center.

The main aim of this project firstly is fixing the corresponding customer demand to a particular retailer or manufacturer or warehouse and secondly, the supplier selection.

Two cases are considered, one where the traditional offline only supply chain is considered and the other where the multiple channels are considered.

A Mixed Integer Linear Programming (MILP) model has been formulated and the optimal solution has been obtained using CPLEX. Each of the two cases is solved twice first, including the customer costs as the objective function and second, including the other objective functions related to the other parts of the supply chain. Solving it for the first time, fixes the corresponding customer demand to a particular retailer or manufacturer or warehouse.

The objective functions are normalized in the second case as the objective function includes the costs and the pollution emissions which are in different units.

Customer's source of purchase, supplier selection and other costs and emission outputs are discussed for 3 cases and 2 risk/ sensitivity analysis cases namely:

i. 3 Cases:

a) Offline only mode

b) Multi-channel mode

c) Multi-channel mode without green objective

ii. 2 risk / sensitivity analysis cases:

d) Multi-channel mode with 5% increase in the price of retailer 1's selling price

e) Multi-channel mode with 20% increase in customer demand

Product Selling Price: The selling price of the manufacturer is less than warehouse which in turn is less than the retailer as the transportation cost is avoided as the entity is far away from the customer.

Table 3.1 Selling price of Products

	1	2	3
Manufacturer	1225	1275	1250
Warehouse	1300	1350	1325
Retailer	1400	1450	1425

Customer Demand over 10 time periods: The customer demand is nil in the first 4 time periods as the time required for the retailer to receive the product is 4 time periods.

Table 3.2 Customer Demand over ten time periods

	1	2	3	4	5	6	7	8	9	10
Customer type c	0	0	0	0	50	0	0	0	0	0
	0	0	0	0	0	50	0	0	0	0
	0	0	0	0	0	0	75	0	0	0
	0	0	0	0	0	0	0	50	0	0
	0	0	0	0	0	50	0	0	0	0
Customer type d	0	0	0	25	0	0	0	0	0	0
	0	0	0	0	0	50	0	0	0	0
	0	0	0	0	0	0	75	0	0	0
	0	0	0	0	0	0	0	40	0	0
	0	0	0	0	40	0	0	30	0	0
Customer type e	0	0	0	0	0	0	30	0	0	0
	0	0	0	0	0	40	0	0	0	0
	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	75	0	0	0
	0	0	0	0	0	0	0	60	0	0

Moreover it is assumed that the customers return the product to the recycling center as average life of a product is assumed to be 2 time periods.

3.2 MODEL FORMULATION

Non Zero Constraints

The index set that will be used in the model formulation are defined below

h: Supplier

i: Manufacturer

j: Warehouse

k: Retailer

r: Recycling Centre

c: Cheapest of online/offline

d: Customer (prefers online)

e: Customer (prefers offline)

t: Time Period 1,2----T

3.2.1 Model Data

Supplier (h):

S_{max} – Maximum Capacity of raw material

S_{min} – Minimum Capacity of raw material

C_{pu} -Purchasing Cost per Unit of raw material

T_{sup} – Transportation cost between supplier and manufacturer

Manufacturer (i):

Manuf Max: Maximum Quantity of products manufactured

TManuf: Unit transportation cost of moving materials from manufacturer to warehouse

Manuf Cost: Cost of manufacturing per unit item

Warehouse (j):

w_{max}: Maximum capacity limit for storing items in warehouse

wInitInv: Initial inventory of finished items at warehouse

wInvCost: Inventory holding cost per unit of finished product at warehouse

Wcost : Selling price of items at warehouse

wInvCost: Inventory holding cost per unit of product at warehouse

Twor: Unit transportation cost of the finished product from the warehouse to the retailer

Retailer (k):

Rmax: Maximum inventory capacity at retailer

RIntInv: Initial inventory of finished product at retailer

Rcost: Selling price of retailer

RInvCost: Holding cost of product at retailer

RBackCost: Unit backorder cost per unit time at retailer

Customer(c, d, e):

x_a: demand of customer 'c'at time 't'

x_b: demand of customer 'd' at time 't'

x_c: demand of customer 'e' at time 't'

dM: distribution between customer and manufacturer

dW: distribution between customer and warehouse

MTrans: Transportation cost to customer per unit distance from manufacturer

WTrans: Transportation cost to customer per unit distance from warehouse

Recycling Centre: (r)

RecInitInv: Initial inventory at recycling center.

x_{aa}: Quantity returned back by 'c' customer at a later time (t+2)

x_{bb}: Quantity returned back by 'd' customer at a later time (t+2)

x_{cc}: Quantity returned back by 'e' customer at a later time (t+2)

RecMax: Maximum capacity of recycling center

Trecycle: Transportation cost from recycling center to manufacturer.

RecInvCost: Inventory holding cost at recycling center

3.2.2 Model Decision Variables

All variables are non-negative

Supplier:

W: Quantity of raw material ordered from a supplier h

S_{Bin}: Binary variable if supplier h is selected in time period t

Manufacturer:

u: Quantity of raw material transported from supplier to manufacturer.

v: Quantity of raw material reaching manufacturer

x: Quantity of items manufactured in a time period t

y: Quantity transported from manufacturer to warehouse

Warehouse:

Ø: Cumulative inventory in warehouse at end of time period t

z: Number of products transported from warehouse to retailer in time period t

Retailer:

RBO: Cumulative backorder at retailer at end of period t

RInv: Cumulative inventory at retailer at end of time period t

Customer:

CM_a: Binary if customer 'c' gets product from manufacturer 'i' online

CM_b: Binary if customer'd' gets product from manufacturer 'j' online

CWa: binary customer 'c' gets product from warehouse 'j' online

CW_b: binary customer'd' gets product from warehouse 'j' online

CR_a: binary customer 'c' gets product from retailer 'k' offline

CR_b: binary customer 'e' gets product from retailer 'k' offline

Recycling Center:

β: Inventory quantity at the recycling center at the end of time t

S: Quantity transported from recycling center to manufacturer.

Pollution (Green):

P_{oll}: Pollution per unit distance (hi, ji, jk, rj)

Dist: Distance between entities (hi, ji, jk, ri)

vehi :Vehicle capacity between (hi, ji, jk, rj)

3.2.3 Model Constraints and Objective Function

Supplier: (h)

$$w(h,t) \leq s_{max}(h,t) * s_{Bin}(h,t) \qquad (\forall h,t) \qquad (1)$$

$$w(h,t) \geq s_{min}(h) * s_{Bin}(h,t) \qquad (\forall h,t) \qquad (2)$$

The quantity ordered should be greater than the minimum quantity and lesser than the maximum quantity or capacity that can be handled by the supplier.

$$\sum_{h} s_{Bmin}(h,t) = 1 \qquad (\forall t) \qquad (3)$$

For a given time period only one supplier can be employed for supplying the raw materials.

The objective function minimizes the total purchasing cost by

$$\text{Minimize } z_1 = \sum_{h}\sum_{t}\left[c_{pu}(h,t) * w(h,t)\right]$$

Manufacturer: (i)

$$w(h,t) = \sum_{i} u(h,i,t) \qquad (\forall h,t) \qquad (4)$$

The sum of all the raw materials transported from supplier to manufacturer for a given supplier and time period is equal to the quantity ordered from the supplier.

$$\sum_{r} s(r,h,t_{-1}) + \sum_{h} u(h,i,t_{-1}) = v(i,t); \quad (t \geq 2) \qquad (\forall i,t) \qquad (5)$$

$$x(i,t) = v(i,t) \qquad (\forall i,t) \qquad (6)$$

The quantity manufactured by the manufacturer is equal to the number of used products sent by the recycling center and the transported products from supplier to manufacturer assuming one raw material is used to make one product.

$$x(i,t) \leq \text{ManufMax}(i) \qquad (\forall i,t) \qquad (7)$$

The above equation is a capacity constraint constraining the quantity manufactured to be less than the maximum capacity of the manufacturer.

The objective function minimizes the total transportation cost from the supplier to the manufacturer

$$\text{Minimize } z_2 = \sum_h \sum_i \sum_t \left[T_{sup}(h,i) * u(h,i,t)\right]$$

The objective function minimizes the total manufacturing cost involved as follows

$$\text{Minimize } z_3 = \sum_i \sum_t [\text{ManufCost}(i) * x(i,t)]$$

Warehouse: (j)

$$x(i,t) = \sum_j y(i,j,t) + \sum_c CM_a(i,c) * x_a(c,t) + \sum_d CM_b(i,d) * x_b(d,t) \quad (\forall i,t) \qquad (8)$$

The above constraint is a flow constraint which states that the quantity manufactured by a manufacturer is equal to the sum of all the products sent to the warehouse from manufacturer and the quantities supplied to the customers to satisfy the online demands.

$$\varphi(j,t) \leq w_{max}(j) \qquad (\forall j,t) \qquad (9)$$

$$\varphi(j,t-1) + \sum y(i,j,t-1) = \varphi(j,t) + \sum z(j,k,t) + \sum_c CW_a(j,c) * x_a(k,t)$$
$$+ \sum_d CW_b(j,d) * x_b(d,t) \qquad (\forall j,t) \ (t \geq 2) \qquad (10)$$

The above constraint is a flow balance constraint of the inventory in the previous time period and the current time period at the warehouse with the quantities that are transported in and out of the warehouse inventory and the online customer demand.

$$\mathrm{WInitInv}(j) = \varphi(j,1) + \sum z(j,k,1) \qquad (\forall j,t) \quad (t=1) \qquad (11)$$

The above is a constraint to initialize the initial inventory quantity at the warehouse

The objective function minimizes the total transportation cost and the inventory holding cost for each time period as follows

$$\text{Minimize } z_4 = \sum_i \sum_j \sum_t T_{manuf}(i,j) * y(i,j,t) + \sum_j \sum_t \mathrm{WInvCost}(j) * \varphi(j,t)$$

Retailer: (k)

$$\mathrm{RInv}(k,t) \le R_{max}(k) \qquad (\forall k,t) \qquad (12)$$

The above is a capacity constraint constraining the maximum inventory that can be stored at the retailer inventory.

$$\mathrm{RInitInv}(k) + \mathrm{RBO}(k,1) = CR_a(k,c) * x_a(c,1) + \ CR_b(k,e) * x_c(e,1) + \mathrm{RInv}(k,1)$$

$$(\forall k) \quad (t=1) \qquad (13)$$

The above constraint is a flow balance constraint of the inventory and the back order in the previous time period and the current time period at the retailer along with the offline demands of the customers.

$$\mathrm{RInv}(k,t-1) + \sum z(j,k,t-1) + \mathrm{RBO}(k,t) = \mathrm{RInv}(k,t) + \mathrm{RBO}(k,t-1)$$

$$+ CR_a(k,c) * x_a(c,t) + CR_b(k,e) * x_c(e,t) \qquad (14)$$

The above is a constraint to initialize the initial inventory quantity at the retailer

$$\mathrm{RBO}(k,t) = 0 \qquad (15)$$

The backorder at all the time periods at the end of the time horizon should be zero or basically all the customer demands must be satisfied at the end of the time horizon.

$$\sum_{i} CM_a(i,c) + \sum_{j} CW_a(j,c) + \sum_{k} CR_a(k,c) = 1 \qquad (\forall c) \qquad (16)$$

$$\sum_{i} CM_b(i,d) + \sum_{j} CW_b(j,d) = 1 \qquad (\forall d) \qquad (17)$$

$$\sum CR_b(k,e) = 1 \qquad (\forall e) \qquad (18)$$

The above 3 constraints constrain that only one of the online or offline channels should satisfy the customer demands of the particular customer of a particular channel preference type.

$$\text{Minimize } z_5 = \sum_{c}\sum_{i} CM_a(i,c) * x_a(c,t) * [Mcost(i) + (MTrans) + dM(c,i)]$$
$$+ \sum_{c}\sum_{j} CW_a(j,c) * x_a(c,t) * [Wcost(j) + (WTrans) + dW(i,j)]$$
$$+ \sum_{c}\sum_{k} CR_a(k,c) * x_a(c,t) * Rcost(k)$$

$$\text{Minimize } z_6 = \sum_{c}\sum_{i} CM_b(i,d) * x_b(d,t) * [Mcost(i) + (MTrans) + dM(c,i)]$$
$$+ \sum_{d}\sum_{j} CM_b(j,d) * x_b(d,t) + [Wcost(j) + (WTrans) + dW(d,j)]$$

$$\text{Minimize } z_7 = \sum_{e}\sum_{k} CR_b(k,e) * x_c(e,t) * Rcost(k)$$

$$\text{Minimize } z_8 = \sum_j \sum_k \sum_t \mathrm{Twan}(j,k) * z(j,k,t) + \sum_k \sum_t \mathrm{RInvCost}(k) * \mathrm{RInv}(k,t)$$

$$+ \sum_k \sum_t \mathrm{RBackCost}(k) * \mathrm{RBO}(k,t)$$

Recycling Centre :(r)

$$\mathrm{RecInitInv}(r) = \beta(r,1) + \sum_i S(r,i,1) \qquad (t = 1) \quad (\forall r) \qquad (19)$$

The above is a constraint to initialize the initial inventory quantity at the recycling center.

$$\beta(r,t-1) + \sum_c x_{aa}(c,t-1) + \sum_d x_{bb}(d,t-1) + \sum_e x_{cc}(e,t-1)$$
$$= \beta(r,t) + \sum_i S(r,i,t) \qquad (\forall,,r,t)(t \geq 2) \quad (20)$$

The above constraint is a flow balance constraint of the inventory in the previous time period and the current time period at the recycling center with the quantities that are transported in from the customer after the product is used (assuming the customers return the product after 2 time periods of usage) and out of the recycling center to the manufacturer for reuse.

$$\beta(r,t) = \mathrm{RecMax}(r) \qquad (\forall r,t) \qquad (21)$$

The above is a capacity constraint constraining the maximum inventory that can be stored at the recycling center.

$$\text{Minimize } z_9 = \sum_r \sum_i \sum_t T_{recycle}(r,i) * S(r,i,t) + \sum_r \sum_t \mathrm{RecInvCost}(r) * \beta(r,t)$$

$$\text{Minimize } z_{10} = \sum_{h}\sum_{i}\sum_{t} \text{Poll}_{hi}\ \text{Dist}_{hi} \frac{u(h,i,t)}{\text{vehi}(h,i)} + \sum_{j}\sum_{i}\sum_{t} \text{Poll}_{ij}\ \text{Dist}_{ij} \frac{y(i,j,t)}{\text{vehi}(i,j)}$$
$$+ \sum_{j}\sum_{k}\sum_{t} \text{Poll}_{jk}\ \text{Dist}_{jk} \frac{z(j,k,t)}{\text{vehi}(j,k)} + \sum_{r}\sum_{i}\sum_{t} \text{Poll}_{ri}\text{Dist}_{ri} \frac{S(r,i,t)}{\text{vehi}(r,i)}$$

CHAPTER 4 RESULTS AND DISCUSSION

The model formulated is tested for a set of realistic data and the results are discussed. . The intermediate outputs are discussed for the Multi-channel case alone. Customer's source of purchase, supplier selection and other costs and emission outputs are discussed for 3 cases and 2 risk/ sensitivity analysis cases.

For the risk/sensitivity analysis, 5% price increase in retailer 1's selling price is considered because retailer 1 is the source of demand satisfaction for the maximum number of customers in the multi-channel only scenario.

4.1 Multi-Channel Related Intermediate Outputs:

Table 4.1 Quantity manufactured over 10 time periods

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
M1	-	-	-	-	-	100	-	90	-	-
M2	-	35	40	40	40	50	75	-	35	35
M3	-	-	-	25	115	60	75	30	-	-

The total quantity manufactured is more than that supplied because there are products coming from the recycling center to the manufacturer to be repaired and remanufactured.

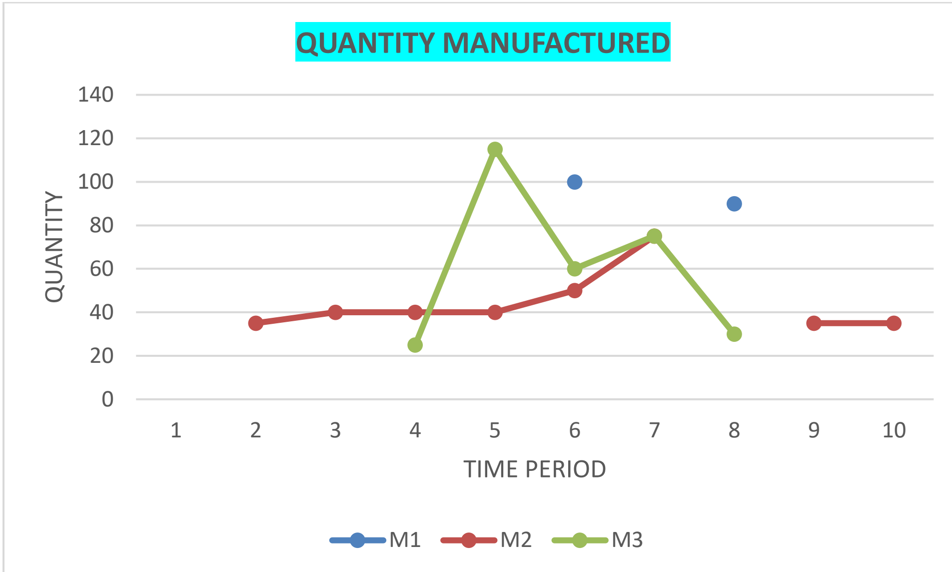

Figure.4.1 Quantity Manufactured

The total quantity manufactured is more than that supplied because there are products coming from the recycling center to the manufacturer to be repaired and remanufactured

Table 4.2 Inventory at Warehouse over 10 time periods

	1	2	3	4	5	6	7	8	9	10
R1	-	-	-	-	-	-	-	-	-	-
R2	-	-	-	-	-	-	-	-	-	35
R3	-	-	-	40	-	-	-	-	-	-

It can be seen in the above table that the storage facilities in the warehouse are unused as the products are transported immediately to the next stage or the customer without the need for storage.

Figure.4.2 Inventory at Warehouse

Table 4.3 Inventory at Recycling Center over 10 time periods

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RC1	-	-	-	-	-	-	-	65	160	250
RC2	-	-	-	-	-	-	-	65	160	289
RC3	-	-	-	-	-	-	-	65	160	289

Inventory at the recycle center remains nil for nearly 7 time periods because a product has to cross through many stages in the supply chain, each step movement of which needs 1 time period and the product life is assumed to be 2 periods. Hence the inventory is unused for 2 more periods after the product reaches the customer. A high level of inventory towards the end is because all the customer-used products reach the recycling center by the end of the time horizon as the time of demand of the customer is such.

Inventory at Retailer over 10 time periods=0

Table 4.4 Quantity transported from Manufacturer to Warehouse

Manufacturer	Warehouse	Time Period	Quantity Transported
2	2	9	35
2	2	10	35
2	3	2	35
2	3	3	40
2	3	4	40
3	3	5	40
3	1	5	65
3	1	6	60

The above table clearly states that there is no movement of products from manufacturer 1 and 4 and the quantity ordered is more or less evenly spaced.

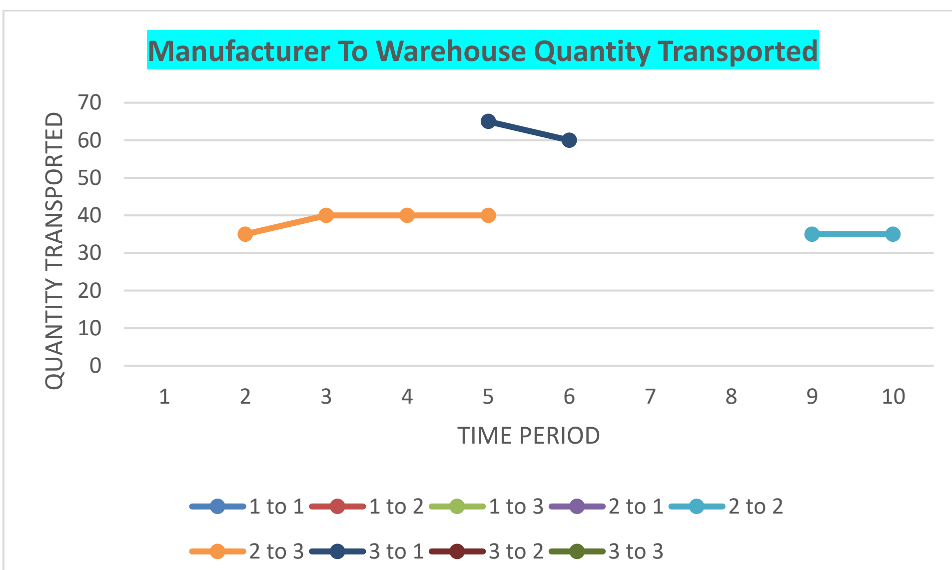

Figure.4.3 Quantity transported from Manufacturer to Warehouse

Table 4.5 Quantity transported from Warehouse to Retailer

Warehouse	Retailer	Time Period	Quantity Transported
1	1	6	65
1	1	7	60
3	1	5	80
3	1	6	40
3	2	3	35

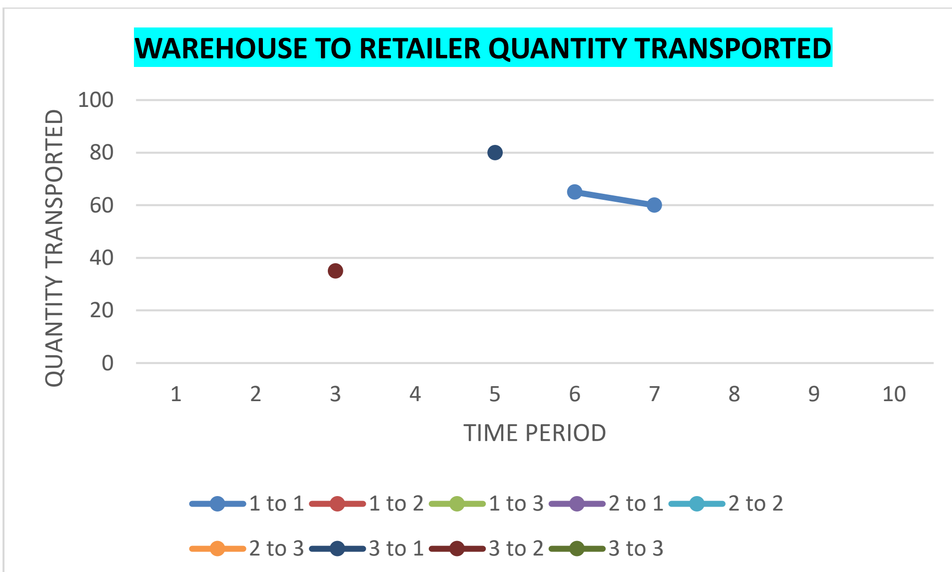

Figure 4.4 Quantity transported from Warehouse to Retailer

The above table clearly states that there is no movement of products from warehouse 2 and 4. The difference between the total quantity transported between manufacturer to warehouse (320) and that from the warehouse to retailer(280) is the same as the total inventory stored in the warehouse which is 40 excluding the 10th time period warehouse inventory(35) as transportation cannot happen from warehouse to retailer after the time horizon has ended.

4.2 CUSTOMERS CHOICE OF BUYING

a) Multi-channel, Multi-channel without green objective, Multi-channel with 20% Demand Increase.

Customer type/ demand 'c'

Table 4.6 Customer type c

Customer	Source of demand satisfaction
1	M3
2	M2
3	M2
4	M1
5	M1

Customer type/ demand'd':

Table 4.7 Customer type d

Customer	Source of demand satisfaction
1	M3
2	M1
3	M3
4	M1
5	M3

Customer type/ demand 'e':

Table 4.8 Customer type e

Customer	Source of demand satisfaction
1	R1
2	R1
3	R1
4	R1

b) Multi- Channel with 5% Increase in Retailer Pricing

Customer type/ demand ‘c’:

Table 4.9 Customer type c

Customer	Source of demand satisfaction
1	M3
2	M2
3	M2
4	M1
5	M1

Customer type/ demand‘d’:

Table 4.10 Customer type d

Customer	Source of demand satisfaction
1	M3
2	M1
3	M3
4	M1
5	M3

Customer type/ demand 'e':

Table 4.11 Customer type e

Customer	Source of demand satisfaction
1	R1
2	R1
3	R1
4	R1
5	R1

c) OFFLINE:

Table 4.12 Customer type Offline

Customer	Source of demand satisfaction
1-15	R1

4.3 AVERAGE PRODUCT COSTS

Average product cost in offline only mode: Rs.1400

Average product cost in multi-channel mode: Rs.1297.35

Average product cost in multi-channel mode with 5% R1 increase: Rs.1305.68

Average product cost in multi-channel mode without green objective: Rs.1297.35

Average product cost in multi-channel mode with 20% demand increase: Rs.1297.35

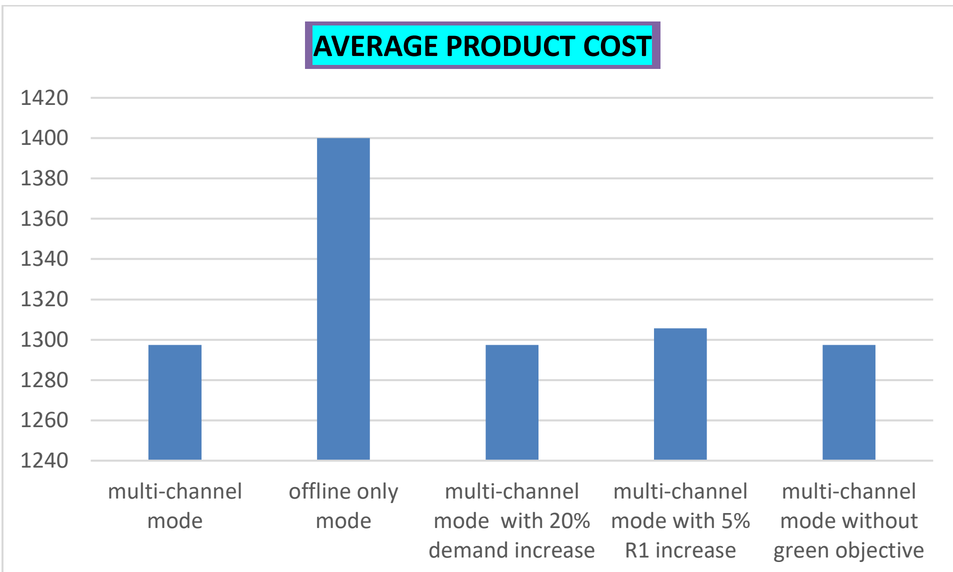

Figure.4.5 Average Production Cost

The customer decision to choose a particular channel especially for the customer types ‘c’ and ‘d’ is based on the tradeoff between the distance and the selling price of the entity selling the product .

4.4 SUPPLIER SLECTION DECISION:

a) Multichannel:

Table 4.13 Selection of Supplier

Supplier	Manufacturer	Time period	Quantity ordered
2	2	1	35
2	2	8	35
2	2	9	35
3	2	2	40
3	2	3	40
3	2	4	40
3	2	5	40
3	2	6	75
3	3	6	75
4	1	7	81
4	1	10	35

Traditional Offline:

Table 4.14 Selection of supplier in off line mode

Supplier	Manufacturer	Time period	Quantity ordered
2	2	1	35
2	2	2	35
2	2	3	35
2	2	4	35
2	2	6	35
2	2	7	35
2	2	8	35
2	2	9	35
4	1	10	35

Multi- Channel with 20% demand increase:

Table 4.15 Multi -Channel with 20% Increase

Supplier	Manufacturer	Time period	Quantity ordered
2	2	1	35
2	2	8	35
2	2	9	35
3	2	2	40
3	2	3	40
3	2	4	40
3	2	5	40
3	2	6	75
3	3	6	75
4	1	7	81
4	1	10	35

Multi-Channel with 5% R1 Price Increase:

Table 4.16 Multi-Channel with 5% R1 Price Increase

Supplier	Manufacturer	Time period	Quantity ordered
2	2	1	35
2	2	8	35
2	2	9	35
3	2	2	40
3	2	3	40
3	2	4	40
3	2	5	40
3	2	6	90

Supplier	Manufacturer	Time period	Quantity ordered
3	3	6	90
4	1	7	105
4	1	10	35

Multichannel without Green Objective

Table 4.17 Multichannel without Green Objective

Supplier	Manufacturer	Time period	Quantity ordered
4	1	1	35
4	1	2	35
4	1	3	35
4	1	4	35
4	1	5	35
4	1	7	85
4	1	8	35
4	1	9	35
4	1	10	35
4	2	6	75
4	3	6	75

The total customer demand and the number of products ordered from the supplier don't add up as there are a lot of products being recycled and the entire supply chain is optimized for a limited number of time periods, hence there are many products at the retailer, warehouse and the manufacturer inventory at the end of the time horizon considered.

4.5 TOTAL QUANTITIES ORDERED, COSTS & EMISSIONS

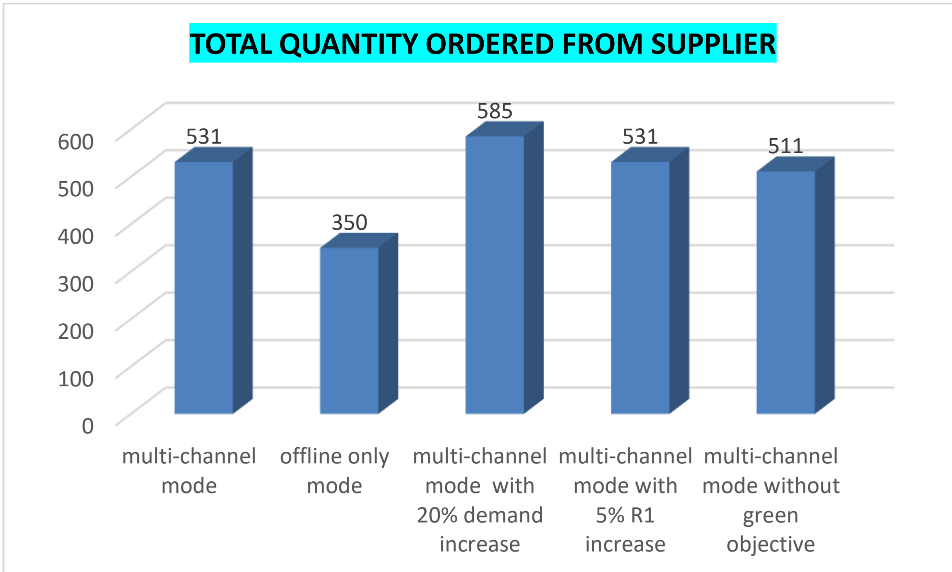

Figure 4.6 Total Quantity ordered from Supplier

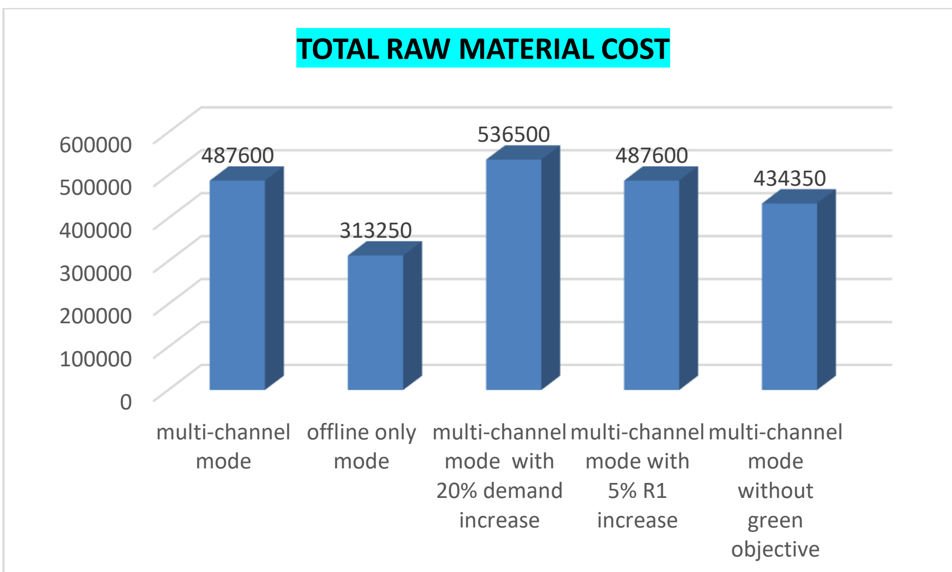

Figure 4.7 Total Raw Material Cost

The total quantity of raw materials ordered from supplier and hence the total supplier cost is comparatively lower for the offline-only mode (34.08%).

Moreover, the total raw material cost and the total quantity ordered form the supplier remains a constant in spite of the increase in the retailer 1's selling price by 5%, but the total quantity ordered increases by 10.17% and the total raw material cost by 10.03% for an increase of 20% customer demand in the multi- channel scenario. When green objective is not considered in the multi- channel scenario, the total quantity ordered decreases by 3.76%.

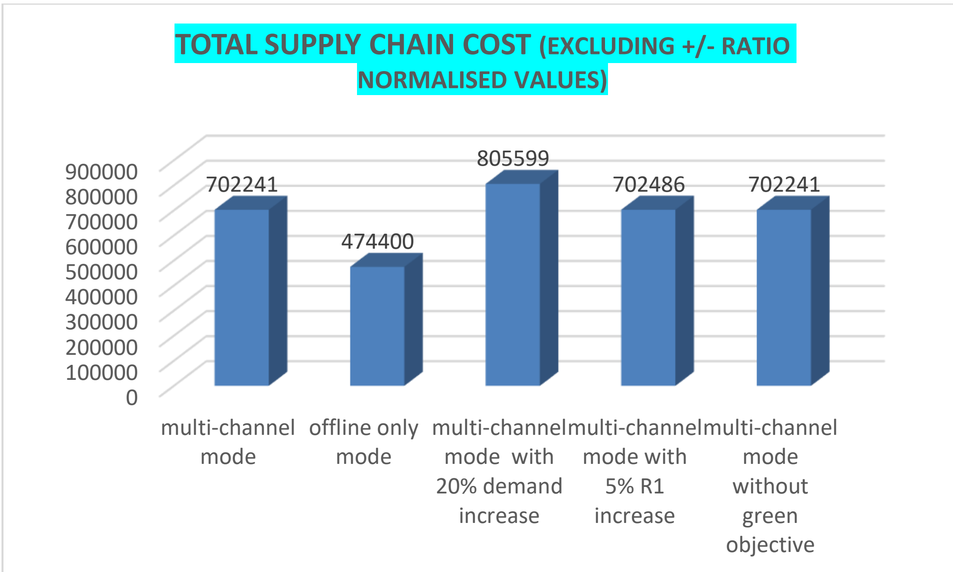

Figure 4.8 Total Supply Chain Cost

Table 4.19 Normalized Objective Function Values

	Normalized Objective Function Values
multi-channel mode	2.085
offline only mode	2.136
multi-channel mode with 20% demand increase	2.101
multi-channel mode with 5% R1 increase	2.11
multi-channel mode without green objective	1

Normalization is done as the objective function includes both cost and emissions both of which have different units.

The percentage increase in total supply chain cost due to an increase of 20% customer demand is 14.72%. Similarly, the increase in the total supply chain cost due to a 5% increase in selling price of retailer 1 is 0.35%. The total supply chain cost decreases by 32.44% for offline only scenario when compared to the multi- channel case whereas, the cost remains the same for the multi -channel case without green objective.

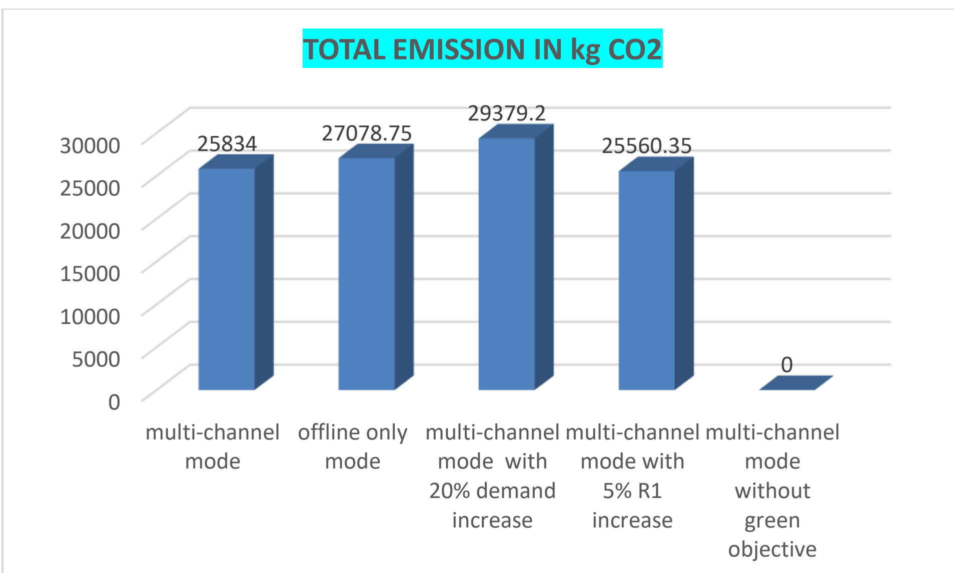

Figure 4.9 Total carbon dioxide Emission in Kg

The total emission in kg CO2 remains more or less a constant for all the cases of supply chain scenarios considered.

CHAPTER 5 SUMMARYAND CONCLUSION

The literature pertaining to areas of interest was reviewed. It was concluded that previous work was done in the areas of supplier selection and supply chain modeling but they did not address both the problems collaboratively. The goal of this thesis was to develop a single integrated collaborative model for a five stage supply chain involving most of the strategic and tactical decisions faced by a real world, such as the selection of the entity that will fulfill the demands of the customer to reduce the total cost incurred to the customer and the supplier selection process integrated with the production amounts, inventory levels, stock-outs and shipment quantities.

5.1 SUMMARY

The five stages considered were Suppliers, Manufacturers, Wholesalers, Retailers and Recycling Centers. Supplier selection process involved choosing of suppliers based on the capacity and cost. Procurement cost was incurred for all the raw materials ordered by the manufacturing plants. Production cost and inter-plant transportation cost was involved at the plant stage. The finished products were shipped to the warehouses using a dedicated mode of transport. Inventory holding cost was incurred at the warehouse stage. This inventory was shipped to the retailers to satisfy the customer's demand. Costs were also incurred for holding inventory and stock outs at the retailers and in the recycling centers too. The used products were collected form the customers and stored in the recycling centers which in turn were supplied to the manufacturer for remanufacturing after repair, hence forming a closed loop supply chain. There were capacity restrictions at every stage of the supply chain.

The primary objective of the problem was to minimize the total cost incurred across all the five stages over multiple time periods and with multiple demands satisfaction channels for the customers and to minimize the total pollution emission related to the transportation across the supply chain.

The underlying assumptions, variables and constraints were defined as per the problem description. This resulted in a mixed integer linear programming problem. The problem was solved with a set of simulated data using the optimization software, CPLEX .The results obtained were tabulated and thus the model implementation was validated accordingly.

5.2 CONCLUSION

As was seen in the results, the customers sometimes prefer a particular offline or online source for buying. But this makes most of the sources obsolete as customers prefer only a select few of all the available options, like warehouses were not used at all and except for retailer 1, the other two were unused, hence reducing their product cost or shutting down of their operations if they can't make profit, reducing the prices should be undertaken for an efficient, lean and cost effective supply chain. If the customer demand increases or the demographics vary, certain other set of sources might be useful and others to be closed down.

Also the average product cost is less in the multi-channel supply chain for the buyers. The total raw materials ordered for the multi-channel case was more than the traditional retail only case. Also, in the retail only case, only one supplier (2) is selected for the major part of the four options available. This implies that the cost of raw material from other suppliers is higher and the customer demand is not that high to use all of them.

The most important significance of this work is that scenarios that can't be visualized clearly due to its practical restrictions can be analyzed by simulating it using this model over various predefined time periods considering multiple channels.

5.2.1 Future Research

The supplier selection was accomplished here based only on two important criteria, i.e. capacity and cost. But as such in the real world, supplier selection is a contract negotiation process involving much more complex criteria. Some of these criterions which have a global impact on the supplier selection process are location proximity, geographic conditions, international exchange rates, foreign trade policies etc. Even though most of them are hard to conceptualize in a mathematical format, at least some of them can be taken into account by considering non-traditional decision making methods such as AHP (Analytical hierarchy process). To make more profit, reducing the prices should be undertaken for an efficient, lean and cost effective supply chain. If the customer demands increases or the demographics vary, certain other set of sources might be useful and others to be closed down. This can be done in the future to make a decision based on many sets of data.

More accurate representation of continuous time periods might be considered unlike the discrete time representation here.Many more objectives can be included and solved as a goal programming problem. The demand from the customers is assumed as deterministic in nature but generally even after extensive market research and forecasting, customer's demand usually ends up being stochastic in nature.

The model was validated using random data and the results were analyzed based on the same. But if available, it would be always interesting to study the effects of actual real world data on the model to help the decision makers to incorporate managerial strategies into their company's core policies.

APPENDICES

Multi-channel CPLEX code

The codes are only for a multi- channel supply chain network

A.1

.mod file

```
//Sets
int Zh=...;
int Zi=...;
int Zj=...;
int Zk=...;
int Zr=...;
int Zc=...;
int Zd=...;
int Ze=...;
int Zt =...;
range h = 1..Zh;
range i = 1..Zi;
range j = 1..Zj;
range k = 1..Zk;
range r = 1..Zr;
range c = 1..Zc;
range d = 1..Zd;
range e = 1..Ze;
range t = 1..Zt;

//Parameters
```

```
int Smax[h]=...;
int Smin[h]=...;
float cpu[h]=...;
int Manufmax[i]=...;
float Tsup[h,i]=...;
float Manufcost[i]=...;
int xa[c,t]=...;
int xb[d,t]=...;
int xc[e,t]=...;
int Wmax[j]=...;
int Winitinv[j]=...;
float Tmanuf[i,j]=...;
float Winvcost[j]=...;
int Rmax[k] =...;
int Rinitinv[k]=...;
float Mcost[i]=...;
float Wcost[j]=...;
float Rcost[k]=...;
float dmc[c,i]=...;
float dmd[d,i]=...;
float dwc[c,i]=...;
float dwd[d,i]=...;
float Wtrans[j]=...;
float Mtrans[i]=...;
float Twar[j,k]=...;
float Rinvcost[k]=...;
float Rbackcost[k]=...;
int Recinitinv[r]=...;
int xaa[c,t]=...;
```

```
int xbb[d,t]=...;
int xcc[e,t]=...;
int Recmax[r]=...;
float Trecycle[r,i]=...;
float Recinvcost[r]=...;
float Pollhi[h,i]=...;
float Pollij[i,j]=...;
float Polljk[j,k]=...;
float Pollri[r,i]=...;
float Disthi[h,i]=...;
float Distij[i,j]=...;
float Distjk[j,k]=...;
float Distri[r,i]=...;
float Vehihi[h,i]=...;
float Vehiij[i,j]=...;
float Vehijk[j,k]=...;
float Vehiri[r,i]=...;
int recyclingcost=...;



//Decision variables
dvar int+ w[h,t];
dvar boolean Sbin[h,t];
dvar int+ u[h,i,t];
dvar int+ v[i,t];
dvar int+ x[i,t];
dvar int+ y[i,j,t];
```

```
dvar boolean Cma[i,c];
dvar boolean Cmb[i,d];
dvar int+ Rbo[k,t];
dvar int+ phi[j,t];
dvar int+ z[j,k,t];
dvar boolean Cwa[j,c];
dvar boolean Cwb[j,d];
dvar boolean Cra[k,c];
dvar boolean Crb[k,e];
dvar int+ Rinv[k,t];
dvar int+ beta[r,t];
dvar int+ s[r,i,t];
dexpr float cost =sum(cc in c,ii in i,tt in t)(Cma[ii,cc]*xa[cc,tt]*(Mcost[ii]+
(Mtrans[ii]*dmc[cc,ii])))+sum(cc in c,jj in j,tt in t)(Cwa[jj,cc]*xa[cc,tt]*(Wcost[jj]
+(Wtrans[jj]*dwc[cc,jj])))+sum(cc in c,kk in k,tt in t)(Cra[kk,cc]*xa[cc,tt]*Rcost[kk])
+ sum(dd in d,ii in i,tt in t)(Cmb[ii,dd]*xb[dd,tt]*(Mcost[ii]+
(Mtrans[ii]*dmd[dd,ii])))+ sum(dd in d,jj in j,tt in t)(Cwb[jj,dd]*xb[dd,tt]*(Wcost[jj]
+(Wtrans[jj]*dwd[dd,jj])))+
sum(ee in e,kk in k,tt in t)(Crb[kk,ee]*xc[ee,tt]*Rcost[kk]);
minimize (cost);
subject to
{
forall(hh in h,tt in t)
{
w[hh,tt]<=Smax[hh]*Sbin[hh,tt];
}
forall(hh in h,tt in t)
{
w[hh,tt]>=Smin[hh]*Sbin[hh,tt];
```

```
}
forall(tt in t)
{
sum(hh in h)(Sbin[hh,tt])==1;
}
forall(hh in h, tt in t)
{
w[hh,tt]==sum(ii in i)(u[hh,ii,tt]);
}
forall(ii in i, tt in t:tt!=1)
{
sum(rr in r)(s[rr,ii,tt-1])+
sum(hh in h)(u[hh,ii,tt-1])==v[ii,tt];
}
forall(ii in i,tt in t:tt!=1 )
{
x[ii,tt]==v[ii,tt];
}
forall(ii in i,tt in t:tt!=1 )
{
x[ii,tt]<=Manufmax[ii];
}
forall(ii in i,tt in t:tt!=1 )
{
x[ii,tt] == sum(jj in j)(y[ii,jj,tt])+sum(cc in c)(Cma[ii,cc]*xa[cc,tt])+
sum(dd in d)(Cmb[ii,dd]*xb[dd,tt]);
}
forall(jj in j,tt in t:tt!=1 )
{
```

```
phi[jj,tt]<=Wmax[jj];
}
forall(jj in j,tt in t:tt!=1&& tt!=2)
{
phi[jj,tt-1]+sum(ii in i)(y[ii,jj,tt-1])==
phi[jj,tt]+sum(kk in k)(z[jj,kk,tt])+
sum(cc in c)(Cwa[jj,cc]*xa[cc,tt])
+sum(dd in d)(Cwb[jj,dd]*xb[dd,tt]);
}
forall(jj in j)
{
Winitinv[jj]==phi[jj,3]+sum(kk in k)(z[jj,kk,4]);
}
forall(kk in k,tt in t:tt!=1 && tt!=2 && tt!=3)
{
Rinv[kk,tt]<=Rmax[kk];
}
forall(kk in k)
{
Rinitinv[kk]+Rbo[kk,4]==sum(cc in c)Cra[kk,cc]*xa[cc,4]+sum(ee in
e)Crb[kk,ee]*xc[ee,4]+Rinv[kk,4];
}
forall(kk in k,tt in t:tt!=1 && tt!=2 && tt!=3 && tt!=4)
{
Rinv[kk,tt-1]+sum(jj in j)(z[jj,kk,tt-1])+
Rbo[kk,tt]==Rinv[kk,tt]+Rbo[kk,tt-1]+
sum(cc in c)(Cra[kk,cc]*xa[cc,tt])+
sum(ee in e)(Crb[kk,ee]*xc[ee,tt]);
}
```

```
forall(kk in k)
{
Rbo[kk,Zt]==0;
}
forall(cc in c)
{
sum(ii in i)Cma[ii,cc]+sum(jj in j)Cwa[jj,cc]+sum(kk in k)Cra[kk,cc]==1;
}
forall(dd in d)
{
sum(ii in i)Cmb[ii,dd]+sum(jj in j)Cwb[jj,dd]==1;
}
forall(ee in e)
{
sum(kk in k)Crb[kk,ee]==1;
}
forall(rr in r)
{
Recinitinv[rr]==beta[rr,6]+sum(ii in i)s[rr,ii,6];
}
forall(rr in r,tt in t:tt!=1 && tt!=2 && tt!=3 && tt!=4 && tt!=5 && tt!=6)
{

beta[rr,tt-1]+(sum(cc in c)xaa[cc,tt-1]+
sum(dd in d)xbb[dd,tt-1]+sum(ee in e)xcc[ee,tt-1])==beta[rr,tt]+sum(ii in i)s[rr,ii,tt];
}
forall(rr in r,tt in t:tt!=1 && tt!=2 && tt!=3 && tt!=4 && tt!=5)
{
beta[rr,tt]<=Recmax[rr];
```

```
}
}
tuple uTuple {
int h1;
int i1;
int t1;
int value;}
{uTuple}uSet={<hh,ii,tt,u[hh,ii,tt]>| hh in h,ii in i,tt in t};
string outputRange;
int numRows;
execute { numRows = uSet.size;
outputRange = "finalyr!M1:" + "M" + (numRows+1);
writeln(outputRange);
}
```

A.2

.dat file

```
SheetConnection File("finalyr.xlsx");
Zh=4;
Zi=3;
Zj=3;
Zk=3;
Zr=3;
Zc=5;
Zd=5;
Ze=5;
Zt=10;
recyclingcost from SheetRead (File, "Sheet1!H1");
Smax from SheetRead (File, "Sheet1!B1:E1");
```

```
Smin from SheetRead (File, "Sheet1!B2:E2");
cpu from SheetRead (File, "Sheet1!B3:E3");
Manufmax from SheetRead (File, "Sheet1!B4:D4");
Tsup from SheetRead (File, "Sheet1!B5:D8");
Manufcost from SheetRead (File, "Sheet1!B9:D9");
 xa from SheetRead (File, "Sheet1!B10:K14");
xb from SheetRead (File, "Sheet1!B15:K19");
xc from SheetRead (File, "Sheet1!B20:K24");

Wmax from SheetRead (File, "Sheet1!B25:D25");
 Winitinv from SheetRead (File, "Sheet1!B26:D26");
Tmanuf from SheetRead (File, "Sheet1!B27:D29");
Winvcost from SheetRead (File, "Sheet1!B30:D30");
Rmax from SheetRead (File, "Sheet1!B31:D31");
Rinitinv from SheetRead (File, "Sheet1!B32:D32");
Mcost from SheetRead (File, "Sheet1!B33:D33");
Wcost from SheetRead (File, "Sheet1!B34:D34");
Rcost from SheetRead (File, "Sheet1!B35:D35");
 dmc from SheetRead (File, "Sheet1!B36:D40");
dmd from SheetRead (File, "Sheet1!B41:D45");
dwc from SheetRead (File, "Sheet1!B46:D50");
dwd from SheetRead (File, "Sheet1!B51:D55");
 Wtrans from SheetRead (File, "Sheet1!B56:D56");
 Mtrans from SheetRead (File, "Sheet1!B57:D57");
Twar from SheetRead (File, "Sheet1!B58:D60");
Rinvcost from SheetRead (File, "Sheet1!B61:D61");
Rbackcost from SheetRead (File, "Sheet1!B62:D62");
 Recinitinv from SheetRead (File, "Sheet1!B63:D63");
xaa from SheetRead (File, "Sheet1!B64:K68");
```

```
 xbb from SheetRead (File, "Sheet1!B69:K73");
xcc from SheetRead (File, "Sheet1!B74:K78");
Recmax from SheetRead (File, "Sheet1!B79:D79");
Trecycle from SheetRead (File, "Sheet1!B80:D82");
Recinvcost from SheetRead (File, "Sheet1!B83:D83");
 Pollhi from SheetRead (File, "Sheet1!B84:D87");
Pollij from SheetRead (File, "Sheet1!B88:D90");
Polljk from SheetRead (File, "Sheet1!B91:D93");
Pollri from SheetRead (File, "Sheet1!B94:D96");
Disthi from SheetRead (File, "Sheet1!B97:D100");
Distij from SheetRead (File, "Sheet1!B101:D103");
Distjk from SheetRead (File, "Sheet1!B104:D106");
Distri from SheetRead (File, "Sheet1!B107:D109");
Vehihi from SheetRead (File, "Sheet1!B110:D113");
Vehiij from SheetRead (File, "Sheet1!B114:D116");
Vehijk from SheetRead (File, "Sheet1!B117:D119");
Vehiri from SheetRead (File, "Sheet1!B120:D122");
Cma to SheetWrite (File, "finalyr!F2:J4");
Cmb to SheetWrite (File, "finalyr!F6:J8");
Cwa to SheetWrite (File, "finalyr!F10:J12");
Cwb to SheetWrite (File, "finalyr!F14:J16");
Cra to SheetWrite (File, "finalyr!F18:J20");
Crb to SheetWrite (File, "finalyr!F22:J24");
```

A.3

.mod file

```
//Sets
int Zh=...;
```

```
int Zi=...;
int Zj=...;
int Zk=...;
int Zr=...;
int Zc=...;
int Zd=...;
int Ze=...;
int Zt=...;
range h = 1..Zh;
range i =1..Zi;
range j=1..Zj;
range k = 1..Zk;
range r= 1..Zr;
range c = 1..Zc;
range d = 1..Zd;
range e = 1..Ze;
range t = 1..Zt;

//Parameters
int Smax[h]=...;
int Smin[h]=...;
float cpu[h]=...;
int Manufmax[i]=...;
float Tsup[h,i]=...;
float Manufcost[i]=...;
int xa[c,t]=...;
int xb[d,t]=...;
int xc[e,t]=...;
int Wmax[j]=...;
```

```
int Winitinv[j]=...;
float Tmanuf[i,j]=...;
float Winvcost[j]=...;
int Rmax[k] =...;
int Rinitinv[k]=...;
float Mcost[i]=...;
float Wcost[j]=...;
float Rcost[k]=...;
float dmc[c,i]=...;
float dmd[d,i]=...;
float dwc[c,i]=...;
float dwd[d,i]=...;
float Wtrans[j]=...;
float Mtrans[i]=...;
float Twar[j,k]=...;
float Rinvcost[k]=...;
float Rbackcost[k]=...;
int Recinitinv[r]=...;
int xaa[c,t]=...;
int xbb[d,t]=...;
int xcc[e,t]=...;
int Recmax[r]=...;
float Trecycle[r,i]=...;
float Recinvcost[r]=...;
float Pollhi[h,i]=...;
float Pollij[i,j]=...;
float Polljk[j,k]=...;
float Pollri[r,i]=...;
float Disthi[h,i]=...;
```

```
float Distij[i,j]=...;
float Distjk[j,k]=...;
float Distri[r,i]=...;
float Vehihi[h,i]=...;
float Vehiij[i,j]=...;
float Vehijk[j,k]=...;
float Vehiri[r,i]=...;
int recyclingcost=...;
int Cma[i,c]=...;
int Cmb[i,d]=...;
int Cwa[j,c]=...;
int Cwb[j,d]=...;
int Cra[k,c]=...;
int Crb[k,e]=...;


//Decision variables
dvar int+ w[h,t];
dvar boolean Sbin[h,t];
dvar int+ u[h,i,t];
dvar int+ v[i,t];
dvar int+ x[i,t];
dvar int+ y[i,j,t];
dvar int+ Rbo[k,t];
dvar int+ phi[j,t];
dvar int+ z[j,k,t];
dvar int+ Rinv[k,t];
dvar int+ beta[r,t];
dvar int+ s[r,i,t];
```

```
dexpr float cost =((sum(ii in i,jj in j,tt in t)(Tmanuf[ii,jj]*y[ii,jj,tt])+
sum(jj in j,tt in t)(Winvcost[jj]*phi[jj,tt])
+sum(ii in i,tt in t)(Manufcost[ii]*x[ii,tt])+sum(hh in h,ii in i,tt in
t)(Tsup[hh,ii]*u[hh,ii,tt])+
sum(hh in h,tt in t)(cpu[hh]*w[hh,tt])+
sum(jj in j,kk in k,tt in t)(Twar[jj,kk]*z[jj,kk,tt])+
sum(kk in k, tt in t)(Rinvcost[kk]*Rinv[kk,tt])+sum(kk in k,tt in
t)(Rbackcost[kk]*Rbo[kk,tt])
+sum(rr in r,ii in i,tt in t)(Trecycle[rr,ii]*s[rr,ii,tt])+sum(rr in r,tt in
t)(Recinvcost[rr]*beta[rr,tt])
+sum(rr in r,ii in i,tt in t)s[rr,ii,tt]*recyclingcost));
minimize (cost);
subject to
{
forall(hh in h,tt in t)
{
w[hh,tt]<=Smax[hh]*Sbin[hh,tt];
}
forall(hh in h,tt in t)
{
w[hh,tt]>=Smin[hh]*Sbin[hh,tt];
}
forall(tt in t)
{
sum(hh in h)(Sbin[hh,tt])==1;
}
forall(hh in h, tt in t)
{
w[hh,tt]==sum(ii in i)(u[hh,ii,tt]);
```

```
}
forall(ii in i, tt in t:tt!=1)
{
sum(rr in r)(s[rr,ii,tt-1])+
sum(hh in h)(u[hh,ii,tt-1])==v[ii,tt];
}
forall(ii in i,tt in t:tt!=1 )
{
x[ii,tt]==v[ii,tt];
}
forall(ii in i,tt in t:tt!=1 )
{
x[ii,tt]<=Manufmax[ii];
}
forall(ii in i,tt in t:tt!=1 )
{
x[ii,tt] == sum(jj in j)(y[ii,jj,tt])+sum(cc in c)(Cma[ii,cc]*xa[cc,tt])+
sum(dd in d)(Cmb[ii,dd]*xb[dd,tt]);
}
forall(jj in j,tt in t:tt!=1 )
{
phi[jj,tt]<=Wmax[jj];
}
forall(jj in j,tt in t:tt!=1&& tt!=2)
{
phi[jj,tt-1]+sum(ii in i)(y[ii,jj,tt-1])==
phi[jj,tt]+sum(kk in k)(z[jj,kk,tt])+
sum(cc in c)(Cwa[jj,cc]*xa[cc,tt])
+sum(dd in d)(Cwb[jj,dd]*xb[dd,tt]);
```

```
}
forall(jj in j)
{
Winitinv[jj]==phi[jj,3]+sum(kk in k)(z[jj,kk,4]);
}
forall(kk in k,tt in t:tt!=1 && tt!=2 && tt!=3)
{
Rinv[kk,tt]<=Rmax[kk];
}
forall(kk in k)
{
Rinitinv[kk]+Rbo[kk,4]==sum(cc in c)Cra[kk,cc]*xa[cc,4]+sum(ee in
e)Crb[kk,ee]*xc[ee,4]+Rinv[kk,4];
}
forall(kk in k,tt in t:tt!=1 && tt!=2 && tt!=3 && tt!=4)
{
Rinv[kk,tt-1]+sum(jj in j)(z[jj,kk,tt-1])+
Rbo[kk,tt]==Rinv[kk,tt]+Rbo[kk,tt-1]+
sum(cc in c)(Cra[kk,cc]*xa[cc,tt])+
sum(ee in e)(Crb[kk,ee]*xc[ee,tt]);
}
forall(kk in k)
{
Rbo[kk,Zt]==0;
}
forall(rr in r)
{
Recinitinv[rr]==beta[rr,6]+sum(ii in i)s[rr,ii,6];
}
```

```
forall(rr in r,tt in t:tt!=1 && tt!=2 && tt!=3 && tt!=4 && tt!=5 && tt!=6)
{

beta[rr,tt-1]+(sum(cc in c)xaa[cc,tt-1]+
sum(dd in d)xbb[dd,tt-1]+sum(ee in e)xcc[ee,tt-1])==beta[rr,tt]+sum(ii in i)s[rr,ii,tt];
}
forall(rr in r,tt in t:tt!=1 && tt!=2 && tt!=3 && tt!=4 && tt!=5)
{
beta[rr,tt]<=Recmax[rr];
}


}
tuple uTuple {
int h1;
int i1;
int t1;
int value;}
{uTuple}uSet={<hh,ii,tt,u[hh,ii,tt]>| hh in h,ii in i,tt in t};
string outputRange;
int numRows;
execute { numRows = uSet.size;
outputRange = "finalyr!M1:" + "M" + (numRows+1);
writeln(outputRange);
}
tuple sTuple {
int r1;
int i2;
int t2;
int value2;}
```

```
{sTuple}sSet={<rr,ii,tt,s[rr,ii,tt]>| rr in r,ii in i,tt in t};
string outputRange2;
int numRows2;
execute { numRows2 = sSet.size;
outputRange2 = "finalyr!N1:" + "N" + (numRows2+1);
writeln(outputRange2);
}
tuple yTuple {
int i3;
int j3;
int t3;
int value3;}
{yTuple}ySet={<ii,jj,tt,y[ii,jj,tt]>| ii in i,jj in j,tt in t};
string outputRange3;
int numRows3;
execute { numRows3 = ySet.size;
outputRange3 = "finalyr!O1:" + "O" + (numRows3+1);
writeln(outputRange3);
}
tuple zTuple {
int j4;
int k4;
int t4;
int value4;}
{zTuple}zSet={<jj,kk,tt,z[jj,kk,tt]>| jj in j,kk in k,tt in t};
string outputRange4;
int numRows4;
execute { numRows4 = zSet.size;
outputRange4 = "finalyr!P1:" + "P" + (numRows4+1);
```

```
writeln(outputRange4);
}
```

A.4

.dat file

```
SheetConnection File("finalyr.xlsx");
Zh=4;
Zi=3;
Zj=3;
Zk=3;
Zr=3;
Zc=5;
Zd=5;
Ze=5;
Zt=10;
recyclingcost from SheetRead (File, "Sheet1!H1");
Smax from SheetRead (File, "Sheet1!B1:E1");
Smin from SheetRead (File, "Sheet1!B2:E2");
cpu from SheetRead (File, "Sheet1!B3:E3");
Manufmax from SheetRead (File, "Sheet1!B4:D4");
Tsup from SheetRead (File, "Sheet1!B5:D8");
Manufcost from SheetRead (File, "Sheet1!B9:D9");
 xa from SheetRead (File, "Sheet1!B10:K14");
xb from SheetRead (File, "Sheet1!B15:K19");
xc from SheetRead (File, "Sheet1!B20:K24");

Wmax from SheetRead (File, "Sheet1!B25:D25");
```

```
 Winitinv from SheetRead (File, "Sheet1!B26:D26");
Tmanuf from SheetRead (File, "Sheet1!B27:D29");
Winvcost from SheetRead (File, "Sheet1!B30:D30");
Rmax from SheetRead (File, "Sheet1!B31:D31");
Rinitinv from SheetRead (File, "Sheet1!B32:D32");
Mcost from SheetRead (File, "Sheet1!B33:D33");
Wcost from SheetRead (File, "Sheet1!B34:D34");
Rcost from SheetRead (File, "Sheet1!B35:D35");
 dmc from SheetRead (File, "Sheet1!B36:D40");
dmd from SheetRead (File, "Sheet1!B41:D45");
dwc from SheetRead (File, "Sheet1!B46:D50");
dwd from SheetRead (File, "Sheet1!B51:D55");
 Wtrans from SheetRead (File, "Sheet1!B56:D56");
 Mtrans from SheetRead (File, "Sheet1!B57:D57");
Twar from SheetRead (File, "Sheet1!B58:D60");
Rinvcost from SheetRead (File, "Sheet1!B61:D61");
Rbackcost from SheetRead (File, "Sheet1!B62:D62");
Recinitinv from SheetRead (File, "Sheet1!B63:D63");
xaa from SheetRead (File, "Sheet1!B64:K68");
 xbb from SheetRead (File, "Sheet1!B69:K73");
xcc from SheetRead (File, "Sheet1!B74:K78");
Recmax from SheetRead (File, "Sheet1!B79:D79");
Trecycle from SheetRead (File, "Sheet1!B80:D82");
Recinvcost from SheetRead (File, "Sheet1!B83:D83");
 Pollhi from SheetRead (File, "Sheet1!B84:D87");
Pollij from SheetRead (File, "Sheet1!B88:D90");
Polljk from SheetRead (File, "Sheet1!B91:D93");
Pollri from SheetRead (File, "Sheet1!B94:D96");
Disthi from SheetRead (File, "Sheet1!B97:D100");
```

```
Distij from SheetRead (File, "Sheet1!B101:D103");
Distjk from SheetRead (File, "Sheet1!B104:D106");
Distri from SheetRead (File, "Sheet1!B107:D109");
Vehihi from SheetRead (File, "Sheet1!B110:D113");
Vehiij from SheetRead (File, "Sheet1!B114:D116");
Vehijk from SheetRead (File, "Sheet1!B117:D119");
Vehiri from SheetRead (File, "Sheet1!B120:D122");
Cma from SheetRead (File, "finalyr!F2:J4");
Cmb from SheetRead (File, "finalyr!F6:J8");
Cwa from SheetRead (File, "finalyr!F10:J12");
Cwb from SheetRead (File, "finalyr!F14:J16");
Cra from SheetRead (File, "finalyr!F18:J20");
Crb from SheetRead (File, "finalyr!F22:J24");
uSet to SheetWrite (File, "finalyr2.0!A1:D120");
sSet to SheetWrite (File, "finalyr2.0!H1:K90");
v to SheetWrite (File, "finalyr2.0!N1:W3");
x to SheetWrite (File, "finalyr2.0!M7:V9");
ySet to SheetWrite (File, "finalyr2.0!A125:D215");
zSet to SheetWrite (File, "finalyr2.0!H125:K215");
phi to SheetWrite (File, "finalyr2.0!M12:V14");
beta to SheetWrite (File, "finalyr2.0!M17:V19");
Rinv to SheetWrite (File, "finalyr2.0!M22:V24");
```

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