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A collaborative framework in outbound logistics for the us automakers

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A COLLABORATIVE FRAMEWORK IN OUTBOUND LOGISTICS FOR THE US AUTOMAKERS

by

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DISSERTATION

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DEDICATION

To my father Professor Md. Yunus and mother Lutfunnesa Yunus
for encouraging me from my very childhood and continuously reminding me and praying for me to earn this PhD degree

&

To my wife Farzana Ferdous (Shonku), Daughter Samin Hassan and Son Safaat Hassan
for grooming my childhood dream with their love, prayers, and unconditional support; their understanding, innumerable sacrifices, and patience that helped me make my PhD dream a reality

.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

ASI - Advanced shipping information

Auto-Carrier Transportation (ACT)

BT - Backorder Time

DT - Dwell Time

EBS - Expedited Backorder Shipments

ET - Expediting Threshold

FCA – Total Fixed Cost of Selecting Arcs

FCPS – Total per Shipment Fixed Cost

FIHC – Total Cost of Facility Inventory Holding

FRL - Full Rail Load

ILP - Integer Linear Programming

ITHC – Total Cost of In-transit Inventory Holding

LS - Lost Sales

LRL - Less than Rail Load

LT - Lead Time

MCNF – Minimum Cost Network Flow

MC – Mixing Center

MIP - Mixed Integer Programming

MILP - Mixed Integer Linear Programming

NAOM - North American Order Management

NFP - Network Flow Planning

OD Pair – Origin-Destination Pair

OEM – Original Equipment Manufacturer

OLRN - Outbound Logistics Rail Network

PT - Patience Time

RC - Rail Carrier

RBS - Regular Backorder Shipments

SPNDLS - Single Product Network Design with Lead-time and Safety Stock

TH - Truck Hauler

TRPC – Total Transportation Variable Cost

TT - Transportation Time

QVC – Quality Verification Check

WCP - Warehouse Consolidation Problem

3PL – 3rd Party Logistics

CHAPTER 1

INTRODUCTION

1.1 Introduction

The automotive industry has shifted permanently to a global competition in the early 21st century. The annual vehicle demand in North American market was declining in the past years. The North American market demand declined nearly 6 million vehicles from 2000 to 2010 (Figure 1.1). As a result, the traditional “Big Three” US Automakers known as General Motors (GM), Ford Motor Company, and Chrysler was losing market share since 2000.

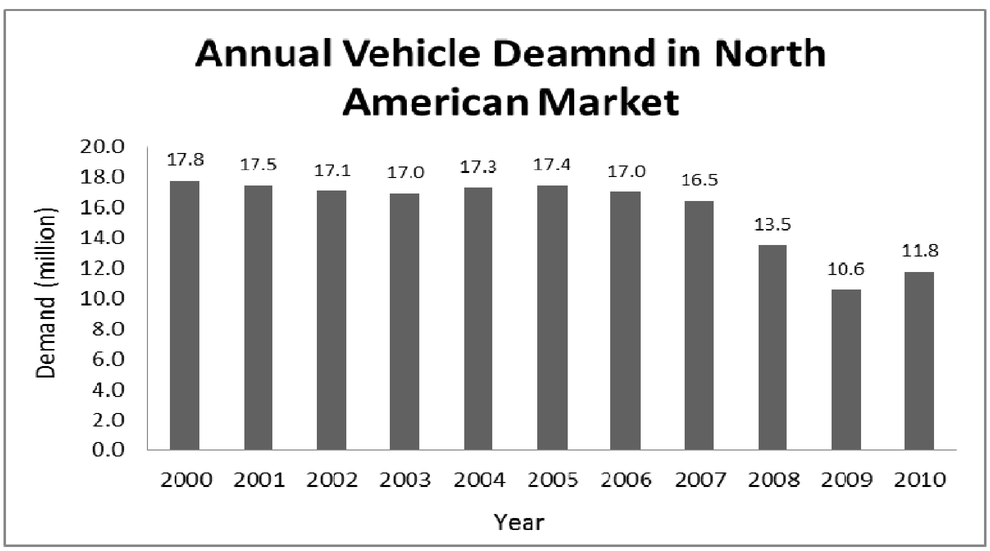


Figure 1.1: Annual vehicle demand in North American Market (Source: WardsAuto.com)

According to WardsAuto.com, General Motors market share fell from 28% in 2000 to 18.8% in 2010; Ford Motors market share fell from 22.6% in 2000 to 16.4% in 2010; and Chrysler market share fell from 14.2% in 2000 to 9.2% in 2010 (Figure 1.2).

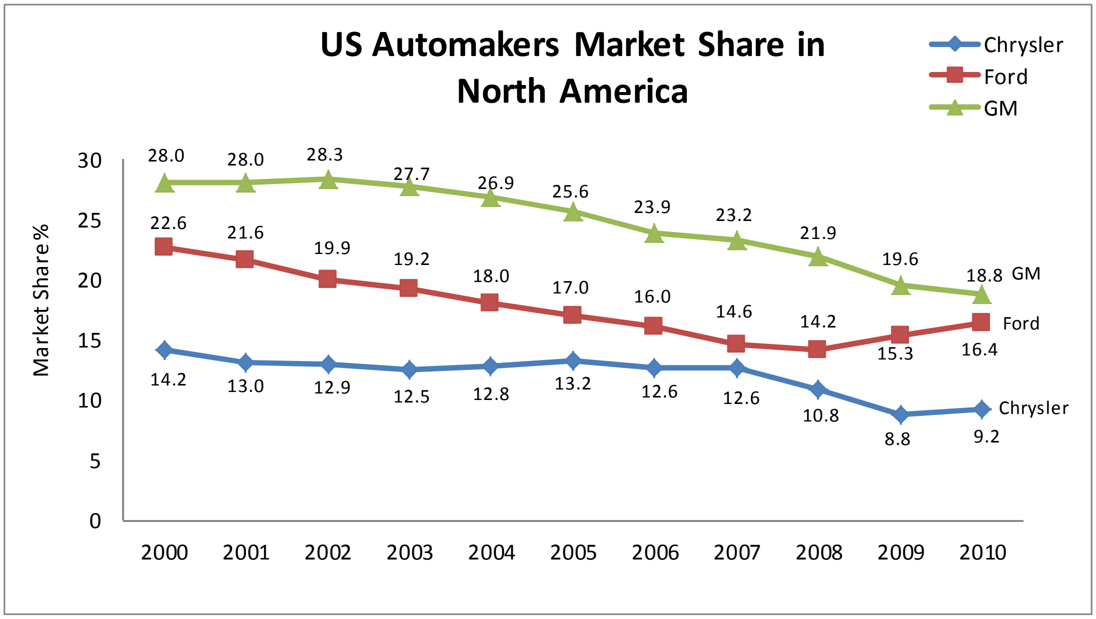


Figure 1.2: US Automaker's combined market share in North America(Source: WardsAuto.com)

The high healthcare costs, skyrocketed gasoline price, increasing raw material cost, slow economic growth etc. are vital few to change North American automotive industry dynamics. The business model that better served "Big Three" US Automakers for decades became no longer effective and sufficient to stay profitable in the past years. The consumer demand shifted from big trucks and SUVs' to small and more fuel-efficient vehicles' such as cars and crossovers.

The "Big Three" US Automakers fell behind the foreign competitors' in responding to the shift in customers' demand (Figure 1.3). The combined market share of Ford, GM, and Chrysler in the North American market fell from 64.7% in 2000 to 44.5% in 2010. On the other hand, the market share of Toyota, Honda, and Hyundai increased from 17% in 2000 to 30.2% in 2010.

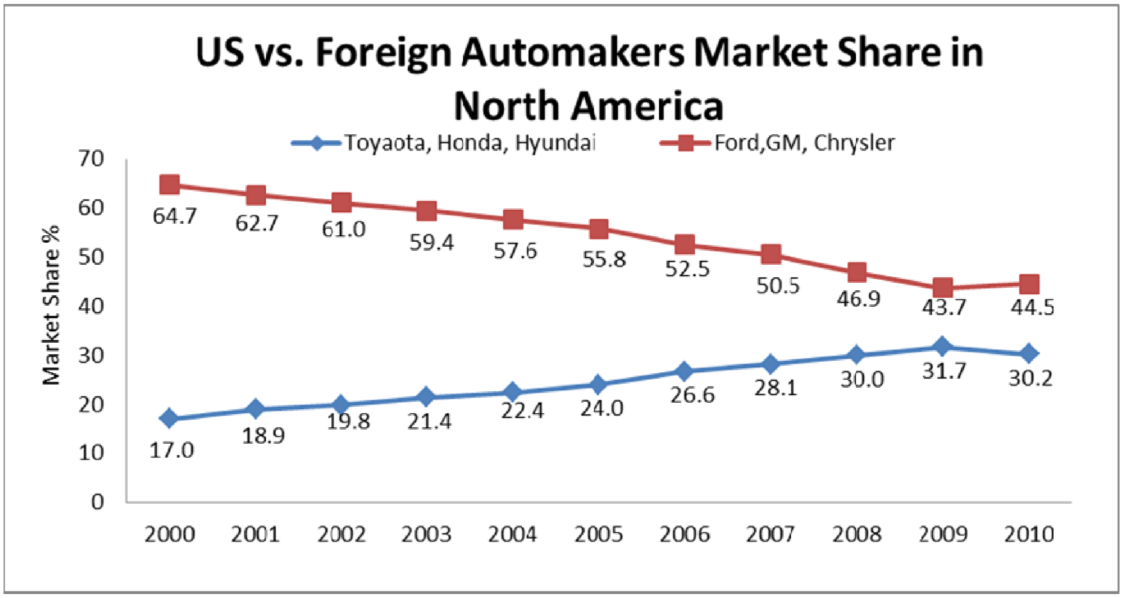


Figure 1.3: US vs. Foreign Automaker's Market Share in North America (Source: WardsAuto.com)

Continuing loss of market share to foreign competitors' in the past years alarmed the US Automakers. Operational efficiency and cost optimization initiatives in all business units became critical for the US Automakers to return to profitability in 2009. Aligning production and manpower capability with a more realistic business plan became eminent for them to retain consumers, and preserve shareholders' and investors' confidence.

Realizing the business dynamics, the US Automakers started developing and marketing exciting, fuel efficient and superior quality cars and crossovers in order to bring North American automotive business to profitability in the last couple of years. They identified that restructuring of capacity, head-count reductions, and alignments of product mix in the global market are, indeed, the right business decisions. In the last couple of years this is what they have done to turn the wheel around. The goal was to manufacture vehicles that the customers love and want. In fact, they acted faster and more efficient way to re-align their product line to the new market demand by predominantly focusing on accelerating new and exciting product development, manufacturing capacity alignment, salaried and hourly work-force and capital reduction through consolidation and closing of manufacturing operations. The result speaks louder as GM and Chrysler paid down their debt to the government and as GM, Ford, and Chrysler made profit in 2010 for the first time since early 2000.

However, further cost reductions through efficient inbound and outbound logistics operations are possible. With the fluctuating production volumes, the efficiency of outbound vehicle distribution operations has been fluctuating as well. Therefore, optimization of outbound logistics operations through consolidation and collaboration among OEMs has tremendous potential to contribute to the profitability by lowering the cost of transportation, in-house inventory, transportation time, and facility costs. The collaboration in the intra- and inter-OEM outbound logistics operations is a critical area that the US automakers need to pay attention and prioritize in their cost reduction initiatives.[1]

[1] Inter-OEM collaboration corresponds to the distribution of production of multiple plants belonging to the same OEM. This includes different brand names of the OEM as well. In comparison, Inter-OEM collaboration refers to the distribution of the production of multiple OEMs, which are in essence competitors under separate ownership.

1.2 Identification and Significance of the Problem

The cost of finished vehicle distribution in the North American market has being increasing in the past years. In recent years, many truck hauler companies have been forced to close businesses and file for Chapter 11 bankruptcy protections. As a result, the automakers are becoming more and more dependent on the rail carrier companies to transport finished vehicles from the origin to the destination. This trend is also motivated by the increased cost of long haul trucking associated with increased oil prices and driver shortage. On the other hand, the rail companies are facing severe capacity issues requiring huge capital investments on railroad tracks, rail cars, and terminal facilities. At the same time, the rail companies have been expanding their business into the non-automotive sector in the recent years. The rail car shortages, fuel surcharges, and high transportation costs are some of the critical factors that force the US automotive companies to search for ways to keep total cost of finished vehicle distribution low.

The rail carriers are considered as load-driven slow mode of transportation. There is a trade-off between *cost* and *volume* in each shipment of finished vehicles using the rail carrier. In order to gain economies of scale, the rail carriers are required to wait at the assembly plants to accumulate the desired level of vehicles (e.g., batching), which are then transported to either the M*ixing Centers* or to the Ramps. Similarly, the Rail Carriers are asked to wait at the Mixing Centers to accumulate the desired model and level of vehicles, which are then transported to the Ramps. This load-driven waiting time increases the in-house inventory at the origin (e.g., Assembly Plants, Mixing Centers) impacting the delivery *lead-time* of the finished vehicles significantly. The *dwell time* is defined as the total time that a finished vehicle spends at the Assembly Plant or at the Mixing Center which are referred as dwell time at the plant or dwell time at the Mixing Center, respectively. The *lead-time* is the sum of the *dwell times* at the Assembly Plant and at the Mixing Center plus the transportation time from the Assembly Plant to the Mixing Center and the transportation time from the Mixing Center to the Ramp.

There are three levels of decision making in outbound logistics system design, planning and management: strategic, tactical and operational. At the strategic level, the locations of the Mixing Centers, Ramps and their characteristics such as capacities are examples of key decisions. At the tactical level, the routing plans from plants to Mixing Centers, utilization of the Rail-Carriers versus truck haulers, and the contracts with the carriers (rail and trucking) are examples of frequent decisions. At the operational level, the key decisions are the daily or weekly routing of vehicle shipments and load consolidation decisions. In all three levels, the goal is to minimize the total distribution costs while maintaining a certain delivery service level to the dealers. While an OEM can strive to achieve the excellence in all of these three decision making levels, the question remains, how to further improve the utilization of carrier services, the Mixing Center and Ramp operations for economies of scale without compromising speed, quality, and customer service.

We believe that both the intra- and the inter-OEM collaborations in the outbound logistics operations are the right strategies to address the aforementioned question. There are both *tangible cost savings* and *intangible profit increase* opportunities associated with the collaborative vehicle distribution systems. The primary tangible saving opportunity is in the lead-time. The higher the *lead-time*, the higher the distribution cost for the automakers since there is a penalty associated with the delivery lead-time of each vehicle. Hence, the US automakers have the potential to save millions of dollars by reducing distribution *lead-time* even by a day. For example, let's assume that the current North American automotive market demand is 14 million vehicles per year and an average penalty (for delay in distribution lead-time) cost per vehicle per day is $3.50. The penalty cost starts as soon as the vehicle receives gate release status (e.g., dealer takes the ownership) right after the final tests at the manufacturing plants. With 15% market share (2.1 million) and only one-day reduction in the distribution *lead-time*, a major US automaker has the potential savings opportunity of $7.35 million per year in the US market alone. This tangible saving increases in proportion to the reduction of the number of days of the total distribution *lead-time*. The reduction in *lead-time* also results in vehicle insurance savings and reduction in vehicle damage and lowered cost of facilities due to increased utilization. In addition, the rail cars are often used as temporary storage units for the batching process (both at the Assembly Plants and Mixing Centers). With the reduced lead-time, the need for these, rather expensive, rail cars will be lowered and result in savings of capital assets costs.

Increased customer satisfaction through reduced lead-times and the availability of inventory at the dealers' lots are some of the *intangible profit* increase opportunities associated with the collaborative vehicle distribution systems. Distributing vehicles faster than the usual lead-time will also increase the satisfaction of the dealers and final customers waiting for the vehicles already ordered. Each day of the *lead-time*, corresponds to the *inventory unavailability* of a finished vehicle on the dealer lot. The profit increase potential associated with the inventory availability of a vehicle configuration is rather difficult to quantify without an extensive market research and a detailed analysis of the customer behavior. This potential also depends on the vehicle inventory of the dealers in a sales region. Assuming that the daily rate of the likelihood of a customer not buying a vehicle because inventory unavailability is 0.1% then we have 0.1% loss of sale on each vehicle. If average vehicle profit, before the overhead expenditures, is $5,000 and the annual demand is 2.1 million vehicles then it equates to $5,000 x 2,100,000 x (0.001) = $10,500,000 profit opportunity per annum. Hence, the total potential benefit of the collaborative vehicle distribution system to the OEM considered in above examples is more than $17.5 million per year. This excludes the most of the other tangible and intangible benefits.

It is critical that the US automakers develop, design, and implement collaboration strategies to minimize the total outbound distribution costs. To illustrate the framework of such collaboration, we refer to the collaborative vehicle distribution pyramid in Figure 1.4. The pyramid shows that commitments from all levels are required to be in place to design, plan, and implement inter-company and intra-company collaboration systems. Negotiation with the 3PL carriers to fully support the collaboration effort and an optimal design and implementation of an outbound logistics network are imperatives of collaboration in the vehicle distribution systems.

Once design and planning collaboration is complete then specific strategies need to be identified and developed for the implementation and execution of the collaborative vehicle distribution system. Collaboration strategies include consolidation of shipments, sharing of equipment and facilities, and sharing of important information among competing companies.

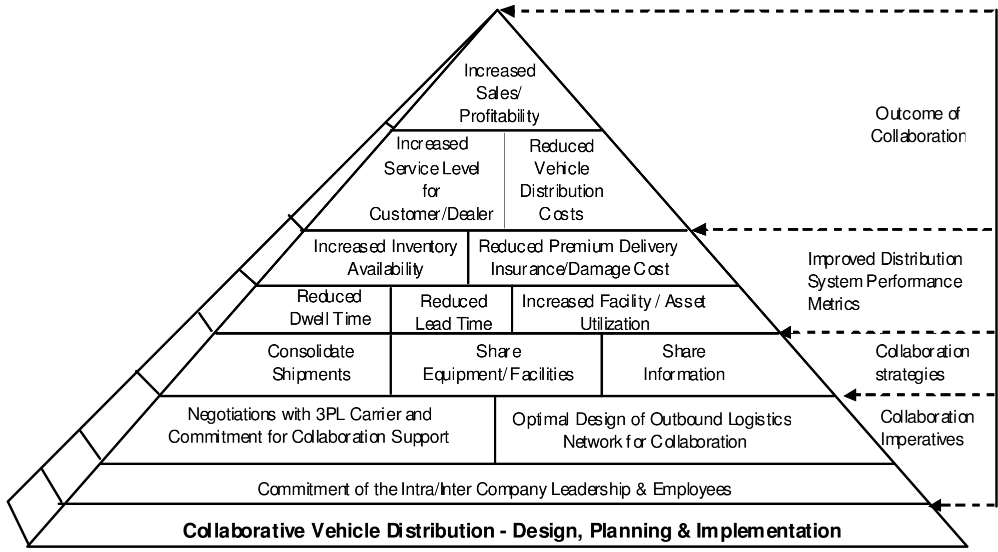


Figure 1.4: Collaborative Vehicle Distribution Pyramid

The consolidation of vehicles under the collaborative framework will ensure higher vehicle availability for batch shipments at the Assembly Plants and at the Mixing Centers. Hence, the proposed collaboration will improve distribution system performance matrix such as reduced dwell time, lead-time, increased railcar asset utilization, and reduced premium deliveries. The reduced *dwell time* at the plant and at the Mixing Centers will not only reduce total distribution *lead-time* of vehicles, but will also increase delivery utilization, decrease premium deliveries of vehicles, and increase the inventory availability of the already assembled vehicle configurations. The primary outcomes as a result of this collaboration are the increased service levels for the dealers and customers, lower vehicle distribution total costs, and higher sales and profitability for all stakeholders including OEMs, carriers, and dealers.

1.3 Research Motivation

The competitive landscape of the U.S. automotive market has transformed from the traditional "Big Three" players to too many viable players. In 2008-2009, the harsh market conditions, excess production capacity, capital asset redundancies, and many inefficient strategies submerged as the roadblocks for the US automakers to stay competitive and profitable in the North American market. In this new competitive era, cross-company collaboration in product development, standardizing and communizing supply base, sharing flexible manufacturing platforms, using common inbound and out bound logistics service providers and warehousing etc. can play vital roles for the US automakers to reduce overall cost and return to profitability. Through the *horizontal collaboration* in the outbound logistics operations, these companies can create close-knit business partnership and act faster than the foreign rivals in delivering finished vehicles at the optimum cost.

Our motivation in this research is driven both from *academic* and *industry* perspectives. In the academic literature, there exists some research on collaboration among competing logistics service providers and carriers. However, the collaboration among competing companies (such as automotive OEMs) in non-core competency operations (e.g., the outbound logistics operations) is yet to be investigated by the academic researchers. The problem of OEM companies' collaboration has different nature and scope than that of the service providers such as carrier companies. Collaboration among competing OEM companies presents different sets of parameters, decision, and constraints such as the facility locations, capacity decisions for assets and facilities, lead-time times and shipment frequency decisions etc. In the case of multiple carriers, the collaboration is mainly driven by the savings associated with economies of scale attained by load consolidation. However, the network decisions (e.g., locations and capacities of facilities) and tradeoffs between shipment frequencies and transportation costs are absent from the carrier level collaboration. In contrast, carriers are bound by the delivery lead-time constraints and the origin and destination of freight movements are not as static as the collaboration among OEMs. Hence, there is clearly a research gap in studying potential outbound logistics collaboration strategies and their benefits for competing OEM companies such as the automotive companies.

In the academic literature on collaboration in automotive industry, many researchers have focused on collaboration in core-competency activities such as collaborative automotive product development (Salhieh 2001), modular manufacturing (Takeishi and Fujimoto 2001), and strategic alliances to manufacture vehicle in the same plant platforms (Brylawski 1999, Segrestin 2005). Our proposed research would contribute to the automotive collaboration literature by studying the collaboration in a non-core operation such as the outbound logistics.

The researches of outbound logistics operations of non-carrier companies have mainly considered *individual companies* working with the *vertical supply chain partners* to improve cost and efficiency of the outbound logistics operation. The researches on outbound logistics related activities include transportation mode selection and customer satisfaction through lead-time reduction (Eskigun*et al.* 2005, Miranda and Garrido 2004, Chopra 2003, Tyworth*et al.* 1998), optimum location of distribution centers (Wasner and Zapfel 2004, Pirkul and Jayaraman 1998, Ebery*et al*. 2000, O'Kelly and Bryan 1998, Racunica and Wynter 2005, Nozick 2001, Melkote and Daskin 2000, Klincewicz 1990, Owen and Daskin 1998, Nozick and Turnquist 2001), and joint replenishment and shipment consolidation (Tyan*et al.* 2003, Pooley and Stenger 1992, Higginson, 1994, Hall 1987, Cetinkaya (2003), etc. Therefore, most of the existing literature focuses on the vertical collaboration in outbound logistics systems. To the best of our knowledge, no academic study studying horizontal collaboration strategies between competing OEMs exist in the literature for outbound logistics operations. Hence, our proposed research contributes the supply chain collaboration literature in this respect.

1.3.1 Why Collaboration is important for US Automakers?

From the industry perspective, we have been witnessing that the US automakers' North American market shares slipped off for the last several years. This downward market conditions and the new market dynamics forced the US automakers adjust their under-utilized assembly plants, reduce material cost, rebalance production schedule, focus on more fuel efficient and customer demand vehicle design, and optimize their dealership networks etc. In 2008-2009, this what the US Automakers mainly focused on and started to see good results as the annual sales and profit margin started going up. The current lower demand of vehicles (approximately 10 million a year today vs. 16.5 million in 2006) manufactured by US automakers resulted in underutilization of the Mixing Centers, the Rail Carriers, and other related assets. As a result, the US automakers closed out and consolidated many Assembly Plants and Ramps. They even have re-configured the entire networks by closing out the Mixing Centers. There are still opportunities and need for re-configuration of the vehicle distribution routes such that through consolidation and facility and asset sharing the delivery lead-times are lowered, overall distribution costs are reduced, and the level of customer and dealer services are increased.

1.3.2 Why MCNF Optimization for OLRN?

To establish an effective and robust collaborative outbound logistics rail network (OLRN), we will be using formal operations research tools and methodologies, which allow us to capture tradeoffs, present in the outbound distribution planning and management. We will also employ the methods of inventory theory to represent the benefits associated with collaboration in outbound logistics system. We will view the collaboration problem from two perspectives: operational collaboration between the multiple plants owned by a single OEM and strategic collaboration among multiple OEMs to attain an integrated outbound logistics network.

1.4 Research Scope

There exists opportunities for both vertical and horizontal collaboration in the outbound vehicle logistics operations in the automotive industry (Figure 1.5). The competing automakers, the competing carrier companies, and the competing dealers have opportunities to form horizontal collaboration within in their respective industries. The contract services such as transportation, transshipments, and consolidation performed by carrier companies for an automaker is a type of vertical collaboration. This type of collaboration is practiced in the automotive industry today.

For example, the Norfolk Southern acts both as a carrier by transporting vehicles and as a 3PL logistics service provider by managing the mixing centers for the Ford

Motor Company's outbound logistics operations. This collaboration between Ford and Norfolk Southern is an example of the vertical collaboration.

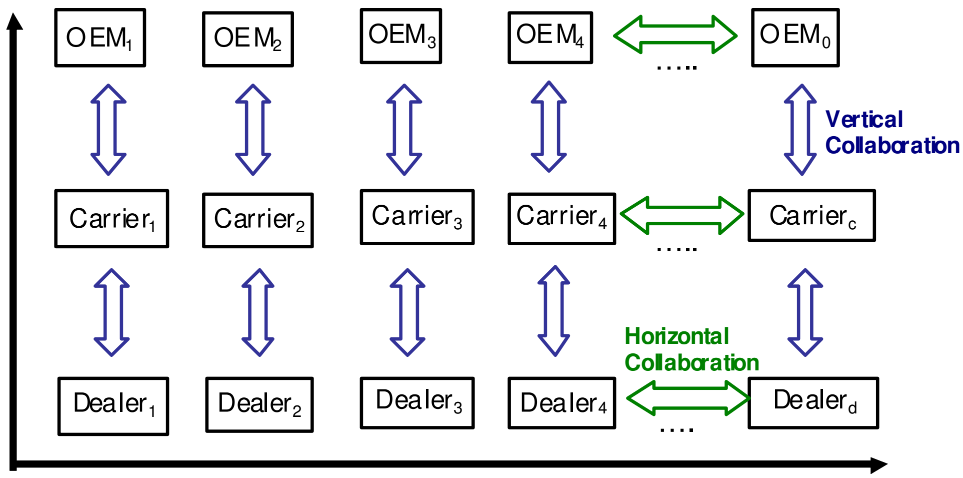


Figure 1.5: Scope of Automotive OL Collaboration (Vertical vs. Horizontal)

To the best of our knowledge, no horizontal collaboration exists in the automotive outbound logistics operation among automotive OEMs today. However, operational level collaboration among automotive dealers' and among carrier companies is practiced in the industry today (Table 1.1). For example, if a customer wants a particular vehicle but it is not available at a dealer's lot then the dealer has the option to check for the vehicle at the other dealers' lot. If the vehicle is found at some other dealer's lot then both the dealers' may exchange the vehicle for another vehicle or split the profit with each other. Also, the dealer may refer the customer to the other dealers. This type of collaboration helps both the dealers to reduce potential lost sales and unsatisfied customers. On the other hand, if a carrier is unavailable to pick a shipment then the automakers have the flexibility to allow another carrier to transport finished vehicles from the manufacturing plants to the dealers. This is mostly practiced on the truck hauler services.

In the outbound logistics operation, about 60% of the finished vehicles are transported from the Assembly Plants to the Mixing Centers using Rail Carrier services. The other 40% of the finished vehicles are transported directly from the Assembly Plants to the dealers via truck hauler services. The truck haulers are also used to transport vehicles from the ramps to the dealers.

	Dealer	OEM	Carrier
Dealer	Collaboration among dealers - operational level exist, does not exist in tactical or strategic level	Dealers and OEMs collaborate by swapping and re-routing the ordered vehicles	Operational level collaboration by expediting the deliveries from ramps and transhipment of vehicles among multiple dealers.
OEM		Inter-OEM and Intra-OEM Collaboration does not exist in operational, tactical, and or strategic level	Tactical and Operational level collaboration between OEMs and Carriers exists as part of vertical integration.
Carrier			Collaboration among carriers in the form of co-loading vehicles in adhoc basis exists in the operational level, no collaboration in tactical or strategic level exist.

Table 1.1: Horizontal Collaboration among competing companies forOutbound Logistics

The delivery of finished vehicles using rail carrier services requires activities such as loading, unloading, and reloading of finished vehicles into the rail cars at the Assembly Plants and at the Mixing Centers. The rail cars are hooked onto the locomotive train and transported to the destination. The delays at the Assembly Plants and at the Mixing Centers due to load make-up queues (for batch completion) contributes significantly to the *lead-time* and distribution cost. There are potentials for cost savings by reducing vehicle distribution lead-time from the Assembly Plants to the Mixing Centers (Eskigun*et* *al.* 2005). Also, there are uncertainties in the accumulation of finished vehicles per destination routes makes it very interesting research topic.

In order to maintain the tractability of our models, we scope our research to the collaboration between US automakers in transporting finished vehicles from the Assembly Plants to the Ramps via Mixing Centers using Rail Carrier services only. As indicated above, given the volume of Rail Carrier shipments, this scope embodies the greatest cost saving potential. We will consider two levels of collaboration in our research: *operational collaboration* and *strategic collaboration*. In the operational collaboration, the Assembly Plants of the same automotive company collaborate with each other through consolidation of vehicles so that the Rail Carriers will not be waiting for load make-up time resulting in reduced *dwell times*. In the strategic level collaboration, the rival US automakers will work together to share strategically located Mixing Centers and or open up new Mixing Centers that are cost and *lead-time* effective.

1.5 Research Objectives

We focus on cost, speed, efficiency, and customer satisfactions as the primary performance matrix of our collaborative vehicle distribution platform. We will use two principal criteria in pursuing this research: i) the research methods and findings will close a gap in the outbound vehicle logistics research literature by proposing a framework for and demonstrate the benefits of the horizontal collaboration, and ii) the logistics practitioners and the managers will find this framework and methodologies are useful and beneficial in practice. The objectives of this research are to develop frameworks and mathematical optimization models for operational and strategic level collaboration.

More specifically, the objectives of this research are to:

1. Develop a framework for outbound logistics collaboration in the automotive industry. This framework will outline three main levels of collaboration: operational, tactical, and strategic. These three collaboration levels require varying levels of commitment, information sharing, and provide different benefits.
2. Develop an operational intra-OEM collaboration model, which optimizes an OEM's logistics *network flow* while accounting for the *lead-times* through inventory model representation as well as cost of lost sales and expediting. This collaboration model can then be used on a regular basis to manage the outbound vehicle distribution. This objective pre-requisites,
    a. Developing a multi-period and multi-product minimum cost network flow (MCNF) base model with ship frequency and off-setting of shipments to represent the outbound logistics system of an OEM.
    b. Develop a feasible solution by integrating the MCNF base model into standard commercial network flow optimization tool ILOG CPLEX.
3. Develop a tactical inter-OEM collaboration model, which jointly optimizes *the flow on logistics networks* of multiple OEMs while accounting for the *lead-times* through an inventory model representation. This collaboration model can then be used for strategic re-design of the existing outbound vehicle distribution networks of multiple OEMs. This objective pre-requisites,

a. Adapting the multi-period, multi-product MCNF model developed in the previous objective for representing the integrated outbound logistics network of multiple OEMs. Develop feasible solution using ILOG.

b. Integrating the inventory model within network design optimization model where, in addition to flow decisions, facility location and sharing decisions are made. Due to discrete nature of the network design model, we will use ILOG CPLEX as the solution engine.

In order to materialize the latter two objectives, we first develop the collaboration framework in Chapter 2. In this framework development, we first map the current-state of the vehicle distribution process of a major US automotive company. We then identify the opportunities in this current state at operational, tactical and strategic levels.

We will implement and test our models in the second objective, via a case study based on Ford's outbound logistics operations. We will collect representative data from Ford and run operational collaboration models in the ILOG environment to compare the base model with the operational collaboration model. The quality measure of our models is the reduction inventory and transportation time, which will be converted to savings in outbound logistics costs. Building a case study for the third set of objectives require data collection from a competitor, which we perceive as a challenging task. In order to study the performance of the models developed for strategic level collaboration, we will also collect representative data from General Motors with which Ford will collaborate. As explained above, we will find a feasible solution using ILOG CLPEX and compare the results with or without strategic collaboration between Ford and GM.

1.6 Dissertation Outline

This dissertation has five Chapters. The organization of the Chapters follows (Figure 1.6). We develop each Chapter based on the previous Chapter starting from Chapter 1. We review corresponding literature to illustrate research gap and our solution approach.

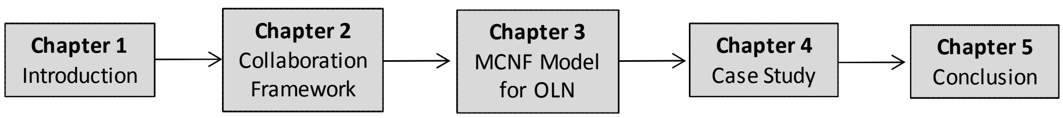


Figure 1.6: Dissertation Roadmap

In Chapter 1, we identify the significance and the need for this research along with the motivation and problem statement. We also identify the current research gap in outbound logistics collaboration between competing companies. The scope of the proposed research and the objectives is outlined in this chapter.

In Chapter 2, we develop a comprehensive collaboration framework. This is one of the key contributions of this research.

In Chapter 3, we develop ship frequency based multi-period, multi-commodity minimum cost network flow base model. In the initial part of the chapter, we develop an approximation of the average number of shipments in a given time unit of a time period. We then develop lemma for non-negativity of inventory at the Assembly Plant and at the Mixing Centers. The lemma was a sufficient condition for average inventory to be positive but not strong enough to ensure non-negativity of inventory in every time units of the time period. In this Chapter, we also used an off-setting strategy such that inventory never goes to negative at the Assembly Plant and at the Mixing Centers with a goal to minimize overall inventory level at a given time unit. We assumed that the inventory at the ramp can be negative as it contributes to the lost sales at the dealer showroom. We developed regression models to approximate the lost sales and corresponding expedited shipments in this chapter.

In Chapter 4, we used case studies to validate the practical application of our model. These case studies illustrate the benefits of outbound logistics collaboration between Ford and GM.

In Chapter 5, we outline the novelty and the key contributions of this research. Finally, we conclude the dissertation by identifying opportunities for future work in the last section of this chapter.

CHAPTER 2

OUTBOUND LOGISTICS COLLABORATION FRAMEWORK

2.1 Introduction

In this chapter, we develop an integrated collaboration framework for the outbound logistics operations of the US automakers. In our framework, we propose three potential levels for the US automakers to form outbound logistics collaboration: operational, tactical, and strategic.

We begin this chapter by understanding the current finished vehicle outbound distribution flow, their related activities, and the associated key performance matrix. We then study the horizontal collaboration and its impact in the automotive industry. In the subsequent section, we illustrate the hierarchical collaboration framework by mapping vehicle and information flow processes of the actual vehicle distribution system. Finally, we concluded the chapter by outlining our proposed research approach and solutions for each form of collaboration.

2.2 Literature Review

Our research proposition is to improve the performance of outbound logistics systems of automotive OEMs by means of horizontal collaboration between plants and competing OEMs. The proposed research thus relates to the literature on logistics system design and management and horizontal collaboration in supply chain management. The performance metrics of an outbound distribution system are time-based metrics (dwell time, lead time) and cost based metrics (transportation cost, servicing cost, inventory cost). The designing and managing of an outbound logistics system requires the use of the above performance metrics differently. The characteristics of the outbound rail logistics systems in the automotive industry can be defined as deterministic (customer demand, servicing times, etc.) whose objectives are independent of random variations. Therefore, classical MCNF models can be used to optimize the decisions.

In this chapter, we study the previous research on horizontal collaboration, logistics and distribution network, consolidation and transshipments in the subsequent sections.

2.2.1 Horizontal Collaboration

To date, there are limited numbers of research papers available on horizontal collaboration (Oum et al. 2004, Cruijssen et al. 2005, and Mason et al. 2007). Most of the collaboration papers out there are qualitative and they have outlined only the general framework of collaboration (Dughertyet *al.* 2006, Finley and Srikanth 2005, Bowersoxet *al.* 2003, Kahn and Mentzer 1996, Sabath and Fontanella 2002). The few quantitative papers that are available in the literature have focused on collaboration among the shippers and the carriers (Groothedde *et al.* 2005), joint replenishment and channel coordination (Chen and Chen 2005), cooperation between shipper and 3PL (Leahy *et al.* 1995) etc. As far as the quantitative papers are concerned, the researchers and practitioners have so long focused on vehicle distribution network optimization models only. The quantitative papers on collaboration among the rival companies in the automotive industry are absent from the literature.

The literature on horizontal collaboration in logistics is scarce. Rival companies form horizontal alliances to gain economies of scale through joint operations, asset utilization, knowledge acquisition, and resource sharing. Oum*et al.* (2004) researched the effect of horizontal alliances on firms' productivity and profitability in the airline companies. The authors outlined that productivity and profitability are functions of the level of cooperation among business partners. The higher the level of cooperation the stronger and positive the productivity and profitability are for each partner. The opportunities and impediments of horizontal cooperation between logistics service providers by Cruijssen*et al.* (2007) and the two-dimensional logistics based strategic alliance among buyer, seller, and third-party service provider by Zinna and Parasuraman (1997) have out lined some significant insights of horizontal collaboration. These papers are rich in qualitative context but they are short in the quantitative data driven analysis of the financial and operational benefits of collaboration.

2.2.2 Logistics and Distribution Network

The design for strategic location of distribution network and the selection of cost effective mode of transportation plays a vital role in improving delivery lead-time, customer services, and transportation cost (Tyworth*et al.* 1998, Eskigun*et al.* 2005, Miranda and Garrido 2004, Chopra 2003). Groothedde*et al*. (2005) studied collaborative inter-modal hub network for the fast moving consumer goods. Eskigun*et al*. (2005) developed a large-scale network model for the outbound supply chain of an automotive company. Melachrinoudis and Min (2007) developed a mixed-integer programming model for warehousing redesign problem. These papers mainly focused collaboration for a specific company and its vertical supply chain partners.

Many researchers studied capacitated and un-capacitated facility location and inter-modal freight hub problems (Wasner and Zapfel 2004, Pirkul and Jayaraman 1998, Ebery*et al*. 2000, O'Kelly and Bryan 1998, Racunica and Wynter 2005, Nozick 2001, Melkote and Daskin 2000, Klincewicz 1990, Owen and Daskin 1998). Jaruphongsa*et al.* (2004) studied a two-echelon dynamic lot-sizing model with constraints such as delivery time window, early shipment penalties, and warehouse space etc. The inherent tradeoffs among facility costs, inventory costs, transportation costs, and customer responsiveness for the location of the Distribution Centers to transport finished vehicles is modeled by Nozick and Turnquist (2001). Mason *et al.* (2003) developed a discrete event simulation integrating WMS (Warehouse Management System) and TMS (Transportation Management Systems). None of these papers have addressed how horizontal companies can be integrated and get benefited.

2.2.3 Consolidation and Transshipments

Many researchers have analyzed different types of freight consolidation policies and their strategies to achieve economies of scale in the logistics and distribution network (Tyan*et al.* 2003, Pooley and Stenger 1992, Higginson, 1994). Hall (1987) introduced three consolidation strategies: inventory consolidation, vehicle consolidation, and terminal consolidation; Cetinkaya (2003) developed a stochastic model on consolidated shipment policies with regards to quantity and time; Herer*et al.* (2002) introduced transshipments technique to enhance both agility and leanness.

Wen *et al.* (2007) used mixed integer programming formulation to model Vehicle Routing Problem with Cross-Docking (VRPCD). Bookbinder and Gumus (2004) used cross docking and shipment consolidation strategy to model an un-capacitated facility location-distribution problem using mixed integer programming. Ratiff*et al*. (2001) developed a mixed-integer linear programming model to determine the number and location of cross-docks in a load driven systems.

However, none of the authors have talked how rival companies in the same industry would get benefits from concepts like consolidation, transshipments, and cross-docking etc. for collaborative outbound logistics systems and distribution network operations.

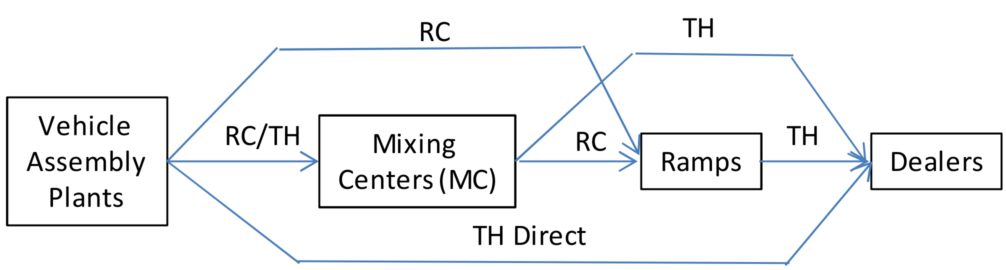
2.3 CurrentState of Automotive Outbound Logistics

The vehicle distribution network of an automotive company consists of all activities require to deliver finished vehicles from the assembly plants to the dealers (Eskigun*et al*. 2005). The planning, scheduling, and distribution of the vehicles to transshipment facilities such as *MixingCenters*and Ramps and to the dealers are a complex network flow problem. Further, aligning market demand to the plant production and plant production to the distribution schedule requires a timely information sharing and continuous coordination among manufacturing plants, dealers, and 3rd party service providers.

Currently, each automotive OEM operates its own outbound logistics network. The outbound logistics operations forms the last step of the three main processes: order receiving from the dealers, manufacturing vehicles at the plants, and transporting finished vehicles to the dealers. In the next section, we describe the key processes of outbound logistics operations and identify the key performance metrics of the outbound logistics system in order to design a robust framework that benefits the automotive OEMs.

2.3.1 Outbound Logistics Process Flow

The outbound logistics process flow begins with the release of finished vehicle from the assembly plant and ends with the arrival of the vehicle to the dealer (Figure 2.1). Some finished vehicles are shipped directly from the assembly plants to the nearby dealers using truck hauler carrier. The rest of the vehicles are shipped via rail carrier to a number of Mixing Centers (MC) where vehicles from several plants are consolidated. In the consolidation process, majority of the finished vehicles are unloaded from the rail cars, staged in the outbound destination lanes for subsequent rail shipment to the ramps. In addition to this mixing process, the Mixing Centers (MC) also play the role of transshipment points where some of the vehicles are re-routed to the ramps without unloading from the rail cars. In addition to rail shipments, some vehicles arriving to the Mixing Centers (MC) are directly shipped to nearby dealers via truck hauler. Once the vehicles arrive to ramps on railcars, they are unloaded and then re-loaded to truck haulers for delivery to dealers.



** Mixing Centers (MC) are also referd as Consolidation Centers, TH for short distant dealers*

Figure 2.1: Vehicle Distribution Flow

In this research, we study only the flow of vehicles from the assembly plants to the Mixing Centers (MC) and then to the Ramps. In studying the flow of vehicles, we consider such distribution performance metrics as waiting time at the facilities (Assembly Plants, Mixing Centers) for batching as well as inventory level, and facility utilization. We map the processes of a major US automotive company, Ford Motor Company, to describe the outbound logistics operations. The General Motors and Chrysler have similar processes in their outbound logistics operations. The definitions of some of the key activities and definitions related to the outbound logistics system are outlined below:

- *Order receiving:* The vehicle orders are received through order fulfillment systems called NAOM (North American Order Management). The vehicle orders are placed by the dealers' through the order bank. On the other hand, active employees and retirees places vehicle orders through the Ford purchasing programs called AXZ-plan and the other individual customer places orders under friends and neighbors called X-plan. Sometimes, dealers also place fanthom orders for hot selling vehicles to increase their shipment quantities for these vehicles. Ford allocates the production to the Assembly Plants based on the orders received. The Assembly Plants sees production schedule 6 days in advance and schedule production accordingly.
- *Manufacturing and shipping:* The vehicles are manufactured at the Assembly Plants according to the production orders. At the end of the production line, finished vehicles go through quality verification checks called QVC. If a vehicle passes QVC test then it goes through the 400 status scanning process known as

“gate release” status. At this point the vehicle is ready to be shipped. In US, the dealer owns the vehicle as soon as it passes the “gate release” status. After receiving gate release status, finished vehicles are driven out of the plant for rough road and water soak test. If a vehicle passes both rough road test and water soak test then it is staged at the designated rail carrier and truck hauler bay lanes for shipment. If a vehicle fails any one of the tests then it is staged at the quality holding area lanes and gets fixed later. It takes about 54 days to deliver a vehicle from order receiving time to the order delivery time. However, the target is to deliver a ordered vehicles within 35 days or less. On the other hand, the average lead-time to deliver a vehicle from the time it receives “gate release status” to the time it is delivered to the dealers is 15 days according to a Ford MP&L manager.

- *Mode of transportation*: The automotive industry uses two modes of transportation in transporting finished vehicles from the assembly plants to the dealers: rail carrier and truck hauler. There are two types of rail cars to transport vehicles from origin to destination, the bi-level and the tri-level rail cars. The bi-level rail car holds in an average 10 vehicles and the tri-level rail cars hold in an average 14 vehicles. The truck haulers hold average 9 to 12 vehicles. Usually, dealers located within 350 miles radius of the manufacturing plants are served by truck hauler services. Any dealers located beyond 350 miles radius are served via combination of rail carriers and truck haulers services. Also, truck hauler services are used for premium shipments of vehicles. The per vehicle transportation cost on truck hauler is higher than the rail. The rail transportation is a low cost mode of transportation. This is why, the automotive companies accumulates finished vehicles at the origin to a certain level and then transport them to the desired destination via rail carrier for economies of scale.

- *Logistics contract terms and conditions*: The US automotive companies have many truck hauler and rail carriers companies to transport finished vehicles from origin to destination. The usual service contract between automotive company and the rail carrier company is about 3 to 5 years. This service contract is subject to be re-negotiable within the terms of the contract. The automotive companies are required to transport a minimum volume of vehicles in each year per the contract agreement. The rail carrier company has the right to request for re-negotiation of the original contract price if an automotive company fails to support the required volume of vehicles as per the contract resulting in revenue shortfall for the rail carrier company. Additional service charges are added for high utilization of the rail carrier. The automaker and the carrier company have 30 days to request for a dismissal of the contract. Some rail carrier company manages all activities including unload, storage, and reload etc. at the Mixing Centers and at the Ramps for the automotive companies. These contracts usually are part of long-term relationships. For instance, the NFS (North Folk Southern) has maintained its contract with Ford Motor Company to manage the Mixing Centers and the Ramps activities for 12 years.

- *Transportation cost*: The transportation cost per vehicle per day varies by distance. The average transportation cost runs from $200 to $500 per vehicle depending on the distance between OD pair distance. The total outbound cost amounts over billions of dollars every year for Ford Motor Company. For any in-transit damages to the vehicles, the automotive companies submit repairs claim against the carrier company. The carrier company pays for the in-transit damages to the vehicles.

2.3.2 Performance Matrix

The automotive companies and the logistics service provider companies keep track of several performance metrics to review, identify, and implement improvement opportunities (Table 2.1). The key performance metrics are categorized into cost, speed, and customer satisfaction. The cost category includes costs such as transportation cost for regular shipments, transportation cost for expedited shipments, service cost for using consolidation center, and in-house inventory carrying cost. There are several measures of "speed." Speed is measured through inventory level at the facility, transportation time, Dwell Time, and Lead Time. The customer satisfaction is impacted by the availability of vehicles at the dealers in a given region. Lost sales as a result of not having the right vehicle at the right dealer at the right time constitute dissatisfied customer. Therefore, Lost Sales is a measure of Customer satisfaction.

The logistics management at the automotive companies and the service provider companies periodically reviews the performance matrices to access cost and delivery robustness. Collaboration among the competing companies will ensure on time performance visibility and require tracking of improvement actions for future follow-up. Collaboration among competing companies will impact inventory label and the vehicle distribution lead-time (speed) by reducing dwell time at the manufacturing plant and at the mixing centers. Therefore, we focus on the reduction of lead-time through the reduction of inventory label i.e. the reduction of dwell times. We believe collaboration among the competing companies will reduce inventory label i.e. dwell time and lead-time reduction. Reducing the distribution lead-time ensures higher utilization of the resources and carriers; reduction of freight and premium freight cost, and ultimately improves customer satisfaction.

2.3.2.1 Dwell Time vs. Inventory

Annual forecasts of the monthly shipping volumes are shared with the rail carrier companies in advance. The carriers are required to be at the origin to pick-up loads for shipments with in ±15 minute's window time (Sherali and Maguire 2000). For economies of scale, the carriers are fully loaded or loaded to a reasonable volume before shipments are made. The process of accumulating vehicles to fully load a rail carrier causes delay at the origin. This delay is called *dwell-time*. The dwell time is the total time a finished vehicle spends at each origin of the distribution network. The dwell time accounts for the significant portion of the vehicle distribution lead-time (Eskigun*et al.* 2005).

Assembly Plant	Carrier (Plant to MC)	Mixing Centers (MC)	Carrier (MC to Ramp)	
- Dwell-time at Plant - Plant inventory - Resource utilization at Plant	- Carrier Utilization - Carrier wait time at Plant -Carrier Service time (Plant to MC)	- Dwell-time at the MC - MC inventory - MC Service cost	- Carrier Utilization - Carrier wait time at MC - Carrier Service time (MC to Ramp)	**Ramp**
Total Lead-time from Plant to Ramp →				

** Mixing Centers (MC) are also referd as Consolidation Centers*

Table 2.1: Performance Matrix for Outbound Logistics Operations

- *Assembly Plant Dwell Time* - The dwell time is the time a finished vehicle spends at the Assembly Plant after receiving the “gate release” status to the time it departs the plant. Eskigun*et al.* (2005) modeled dwell times as function of administrative time, congestion time, and load make-up time. The authors argued that the load-make-up time constitute the majority of the dwell time. Accordingly, the authors, combined load-make-up-time and administrative delays to calculate dwell time. The authors also assumed that the arrivals of vehicles from the production line are uniformly distributed and the carriers carry exact number of vehicles each time. However, the vehicle production rates (for a given sales region) are random, and, in similar real-world settings, we know that customer orders are usually assumed to arrive according to a Poisson distribution. Also, the volume of vehicles a carrier transports varies across different shipments. Hence, the constant estimation of *dwell time* does not represent the dynamic and stochastic nature of the outbound logistics operations.

- *Mixing Center (MC) Dwell Time* - The Mixing Centers *(MC)* are designed to serve as load-driven cross-docks (Ratliff *et al.* 2001). The *dwell time* at the consolidation center is the total time a vehicle spends at the Mixing Center (MC). Upon arrival of the locomotive train at the Mixing Center (MC), vehicles are unloaded and staged onto the lanes for next route delivery. The vehicles are then re-loaded onto the outbound train at the Mixing Center (MC) going to the Ramp.
- *Inventory at a facility* – The time to accumulate a certain batch size creates congestions which constitute dwell time at the facility. This dwell time effects inventory label at a given time unit. The Inventory label is a function of dwell time and the rate of flow. The inventory increases as the dwell time increase, whereas, the inventory label decreases as rate of flow increases.

$$\text{Inventory level} = \text{Dwell time} \times \text{Rate of Flow}$$

2.3.2.2 Lead Time

Lead-time is defined as the total time to deliver a finished vehicle from the time it receives gate release status at the Assembly Plant to the time it is delivered to the dealer(s). The *lead-time* is the sum of the *dwell times* at the Assembly Plant and at the Mixing Center (MC) plus the transportation time from the Assembly Plant to the Mixing Center (MC) and the transportation time from the Mixing Center (MC) to the Ramp.Transportation time is the time vehicle in transit between origins to destination. Lead-time consists of *dwell time* and transportation time (Figure 2.2). One of the objectives of collaboration in outbound logistics is to reduce in-house inventory and lead-time.

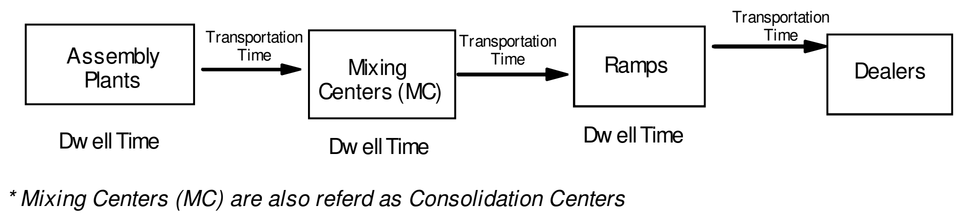


Figure 2.2: Lead-time to deliver vehicles from Assembly Plants to the Ramps

$LT = DT_{Pant} + TT_{Plant\_MC} + DT_{MC} + TT_{MC\text{-}Ramp}$

Where,

LT = Lead Time

DT = Dwell Time

TT = Transportation Time

2.4 Horizontal Collaboration

Today, it is becoming impossible for a company to perform well alone in the rapidly changing business environment. The concept of working with the competing companies is referred as *horizontal collaboration*. The motivation of collaboration is to reduce overall systems cost without shifting them to the partners; instead, it maximizes value for all stakeholders (Finley and Srikanth 2005). The industry leaders who understand collaboration is imperative for their continued success are the biggest advocates of collaboration (Langley 2000). Collaboration enables the competing companies to claim greater success jointly than can be achieved independently

(Daugherty *et al.* 2006). Collaboration brings fundamental shift in the outbound logistics operations of the automotive industry by leveraging and integrating cross company resources. There are opportunities for the US automotive companies to reduce cost and improve customer services significantly in the non-core business operation such as outbound logistics through intra and intercompany collaboration.

The essence of horizontal collaboration is to jointly develop strategic plan and synchronize operations to achieve economies of scale, reduce or eliminate duplication and redundant operations (Bowersox*et al.* 2003). Collaboration requires fundamental changes to the organizational norms and business as usual culture and mindset (Daugherty *et al.* 2006, Finley and Srikanth 2005). The higher the cooperation, the stronger the alliance, and the significant are the productivity and profitability (Oum*et al.* 2004). Through collaboration, the US automakers will be able to share information, processes, lessons learned, best practices, and exchange expertise, knowledge bank and technologies with each other.

2.4.1 Types of Horizontal Collaboration

Colombo and Massimo G. (1998) described two types of horizontal collaboration namely, i) *non-equity* collaboration and ii) *equity* collaboration. The non-equity collaborations are aimed at sharing and optimizing the existing resources while the equity-based collaborations are aimed at venturing new businesses jointly with the competing companies. The non-equity collaborations are the collaborations in the operational level while the tactical and the strategic level collaborations are the equity level collaborations (Table 2.2). Each type and level of collaboration requires varying degree of leadership engagement and commitment.

Types/Levels	Operational	Tactical	Strategic
Non-equity	X		
Equity		X	X

Table 2.2: Relationship of Collaboration Types vs. Levels

The significance of each types of horizontal collaboration is:

- In the *non-equity relations*, the competing companies' will form bi-lateral contractual agreement to effectively share existing distribution facilities and network systems to gain economies of scale and deliver vehicles faster than promised dates.
- In the *equity relations*, the competing companies will jointly open and operate new distribution facilities to reduce overall distribution cost and achieve systems efficiency.

2.4.2 Degree vs. Levels of Horizontal Collaboration

According to Naim *et al.* (2006), "the greater benefits are accrued to those companies that achieve a closer relationship." The level of collaboration varies with the degree of relationship among the competing companies (Figure 2.3). In the operational level, each company focuses on its core competencies but only share the best practices with each other requiring low degree of collaboration. In the tactical level, the companies create co-operative relationship and share resources (equipment, facilities, and expertise) among themselves requiring medium degree (co-operative) of collaboration. In the strategic level, the competing companies establish partnership agreements and develop joint ventures requiring high degree (partnership) of collaboration.

In the automotive industry, the Assembly Plants within the same company will work with each other to consolidate vehicles requiring low degree of relationship. In order to share existing Mixing Centers (MC) with the competing companies will require co-operative relationship. On the other hand, if the US automakers find a strategic location to establish a new Mixing Center (MC) that serves everybody's interest will require high degree of relationship.

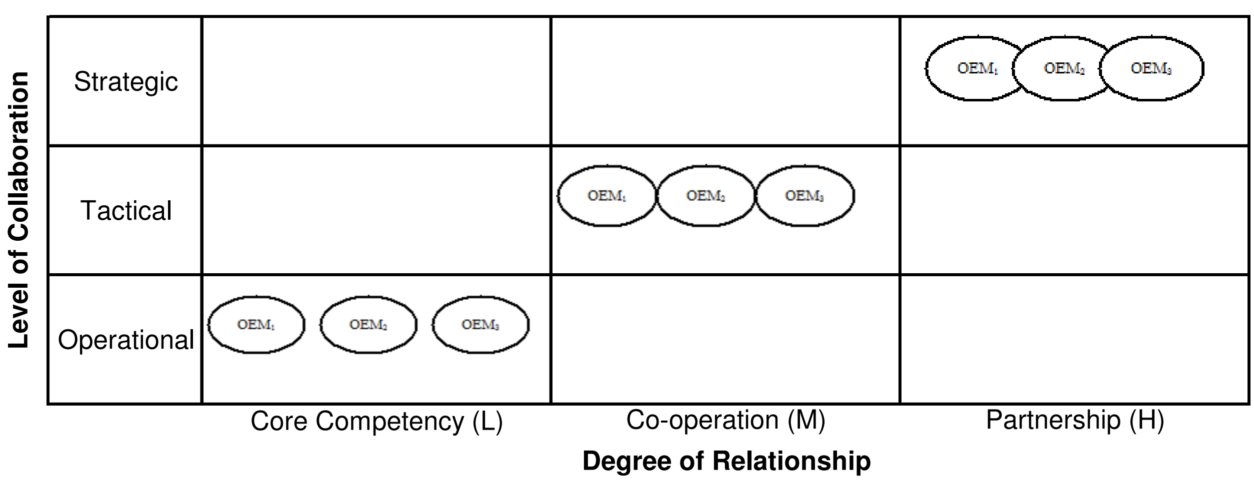


Figure 2.3: Levels of Collaboration vs. degree of relationship (Source: Naim et al. 2006)

2.4.3 Imperatives of Successful Horizontal Collaboration

The most important factors for successful horizontal collaboration are that the competing companies trust each other and work as team players. The success of horizontal collaboration in the automotive industry depends on the strategic alignment of overall goals and objectives of each competing companies goals and objectives. When strategies are aligned, each partner equally recognizes advantage and disadvantage of collaboration (Finley and Srikanth 2005). The contractual terms and conditions and the R&R (roles and responsibilities) of each competing companies need to be detailed out in the collaboration agreement document. The type and extent of data sharing, communication methods, joint planning and implementation procedures, business performance review process, sharing operational expenditures and profits etc. must be clearly outlined so that each partner knows what to expect (Chan *et al.* 2004).

Sharing downstream demand information with the upstream participants is critical to improve collaborative systems response times and overall success (Finley and Srikanth 2005). Communication and information sharing among the partners must be open, accurate, and consistent. The collaborative partners shall determine the speed and period of communication for adequate product flow management. Better visibility such as real-time inventory information will ensure each competing company react quickly (Finley and Srikanth 2005).

For successful collaborative vehicle distribution system, the US automotive companies shall hold regular meetings to monitor progress, re-asses goals and objectives, discuss collaboration outcome, identify action plan to close gaps, and plan for future business opportunities. Regular meetings need to be held at the operating level and infrequently as quarterly meetings to be held at the executive level. Reviews of performance metrics shall beon a regular basis so that the participating firms can adjust goals and take necessary actions to make continuous improvements (Daugherty *et al.* 2006).

Horizontal collaboration in the automotive vehicle distribution system will fail if the terms and conditions are not clearly outlined, partners' resources and capabilities are not aligned, and operational standards and performance metrics are not well defined (Daugherty *et al.* 2006). Lack of trust in each other is a stumbling block of successful collaboration. If the US automotive companies trust each other and work as an extended enterprise then mutually beneficial gains will be realized.

2.5 Outbound Logistics Collaboration Framework

In today's fierce competition, cost reduction through higher utilization of resources and redesigning and improving existing delivery route performance are critical for the US automotive outbound logistics operations. To do so, the logistics practitioners in the automotive industry are under challenge to think differently and adopt fundamental and operational changes to the company's traditional vehicle distribution practices. For this, we propose an innovative collaboration framework and application tools to help the automotive companies to work cohesively in optimizing their outbound vehicle logistics operations. The goal is to minimize in-house inventory level and the transportation time keeping transportation cost low without compromising customers' satisfaction.

Collaboration is like a step function where the collaboration process among competing companies gets maturity in three levels of collaboration, namely operational, tactical, and strategic. In the operational level, the Assembly Plants of the same company will form collaborative partnership among themselves. The operational level collaboration will set the stage and the business culture for the tactical and strategic level collaboration. The tactical and strategic level collaboration will require new business acumen and communication infrastructure. The time line to form operational level collaboration is a short-term one and will take somewhere 1 to 3 months. In the tactical and strategic level, the competing companies will form collaborative partnership. The time to form tactical level collaboration is a mid-term one and will take 3 to 6 months. On the other hand, it takes 9 months to a year to form and execute strategic level collaboration. The tactical level collaboration is a pre-requisite for a successful strategic level collaboration among the competing automotive companies.

We illustrate this hierarchical collaboration framework by mapping vehicle and information flow processes of the actual vehicle distribution system (Figure 2.4). Each box in the framework depicts the process steps and the corresponding bullet points show enabling methods, tools and technologies. In our framework, we propose three potential levels to form collaboration: operational, tactical, and strategic. We will describe the operational definition, research approach, and proposed solution methodology of each levels of collaboration in the successive sections of this chapter.

2.5.1 Operational Level Collaboration

Traditionally, the rail carrier waits at the Assembly Plant until sufficient volumes of vehicles are accumulated before departing for Mixing Centers (MC) or directly for Ramps. This load-driven outbound logistics system results in a high inventory level i.e. higher lead-time and higher distribution cost for the company. Besides, delaying in delivery may cause unavailability of a desired vehicle at the dealers' lot resulting unsatisfied customer and, in some instance, loss of potential sales for the company. On the other hand, if the carrier leaves the Assembly Plant with less than full load due to unavailability of the required vehicles then the carrier may be underutilized. This will result in high unit transportation cost and potential premium shipments of vehicles on a later time. An operational level collaboration at the Assembly Plants and at the Mixing Centers (MC) will balance the wait time cost and the cost of underutilized carriers. In the operational level collaboration, the Assembly Plants of an automotive company will work jointly to take advantage of the economies of scale by consolidating finished vehicles from different Assembly Plants to a cost effective plant. The intent of the operational level collaboration is to consolidate vehicles at one location and dispatch them on a fully loaded carrier.

2.5.1.1 Research Approach

We propose concepts like *shipment consolidation* (Figure 2.4) and *freight consolidation* (Figure 2.5) to make operational level collaboration functional. Through shipment and freight consolidation, *less than railcar-load* (LRL) shipments can be converted to *full railcar-load* (FRL) shipments. For shipment consolidation, finished vehicles from other Assembly Plants are transported to the consolidated Assembly Plant using company own truck hauler or 3PL own truck hauler. At the consolidating Assembly Plant, vehicles from other Assembly Plants are unloaded from the shuttle truck and re-loaded onto the rail cars for shipments. For freight consolidation, the rail carrier picks shipments from one Assembly Plant and then goes to the other Assembly Plants to pick readily waited rail cars full of finished vehicles for same destination MixingCenter. Theconsolidated Assembly Plants are required to be rail connected for freight consolidation strategy to work. Using shipment consolidation, the Nabisco Inc. improved its on-time delivery and reduced its transportation cost by 50% and inventory levels significantly (Quinn 1997).

In Figure 2.6, we develop a process flow for operational level collaboration. In the operational level collaboration, decisions on consolidation Assembly Plants, the OEM makes shipment frequency, and consolidation volume etc. upfront. .Shipment and freight consolidation strategies won't apply when load make-up delays are not a possibility at the manufacturing plant. For inter-OEM collaboration, the Assembly Plants share real-time vehicle volumes and schedule information with each other through intra-net services for effective shipment and freight consolidation.

The outbound logistics operations management required evaluating the performance of OD (origin – destination) pair routes to measure the impact of shipment and freight consolidation strategy. When relative and substantial improvements are made then the existing OD routes are re-configured, re-designed, and underutilized and non-necessary routes and Mixing Centers (MC) are closed.

2.5.1.2 Proposed Solution for operational level collaboration

The objective in the operational level collaboration is to reduce finished vehicles inventory to reduce *dwell-time* at the Assembly Plants and at the Mixing Centers. The *dwell-time* at the Assembly Plant is a major contributor to the total vehicle distribution lead-time from origin (Assembly Plants, MixingCenters) to destination (Mixing Centers, Ramps). Similar to the Postal Service and Airline industry, right design and right planning of shipment and freight consolidation strategies will reduce *dwell-time* significantly and improve *lead-time* and cost for the automotive industry.

2.5.2 Tactical Level Collaboration

The outbound vehicle distribution network of each US automotive companies consists of several Assembly Plants, Mixing Centers (MC), and Ramps. The recent shift in the market demand and the change in the market share resulted in, some instance, underutilized Mixing Centers (MC), Ramps, equipment, and manpower resource for the US automakers. With the downward market demand, the US automotive companies have realigned vehicle production to Assembly Plants and re-configured the distribution networks as well as the routes accordingly. This re-alignment has brought opportunities for the US automotive companies to consolidate facilities and, in some cases, to close Ramps and Dealership. In this section, we propose tactical level collaboration as a first step strategy for the competing US automotive companies to collaborate on vehicle distribution systems. Under this strategy, the US automotive companies will have the opportunity to share some of the underperforming but strategically located Mixing Centers (MC) and Ramps with each other and help further reduce cost and maximize systems efficiency.

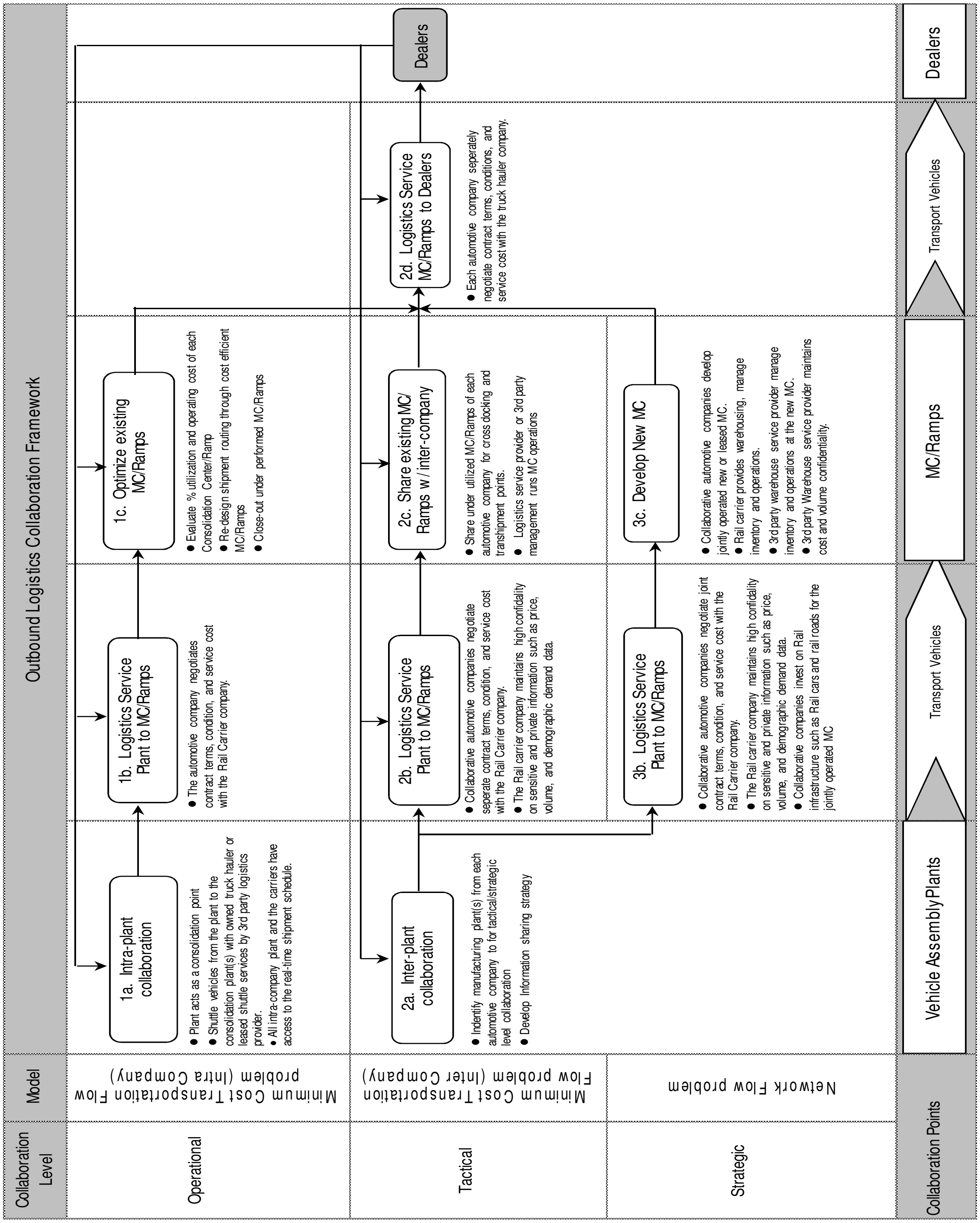
2.5.2.1 Research Approach

We propose techniques such as transshipments and vehicle consolidation strategies for the tactical level collaboration. For transshipments, one automaker will use the underutilized and strategically located current Mixing Center (MC) to switch rail cars from one carrier to another. At the transshipment location, unloading, staging, and re-loading activities are not required for the transshipment vehicles keeping dwell time at minimum. For consolidation, one automaker will share existing but underutilized Mixing Center (MC) with the competing automakers.

Consolidation will require activities such as unloading, staging, and reloading of vehicles and these activities varies by destination route schedule from the consolidated Mixing Centers (MC) to the Ramps. We believe that the consolidation of vehicles at the competing company Mixing Centers (MC) will improve current vehicle transportation time by reducing the load –make-up wait time significantly and minimize total outbound logistics cost for all collaborative companies.

In Figure 2.8, we develop a process flow to aid the US automotive companies decide when and in what condition to share Mixing Centers (MC), Ramps, and rail carrier services for mutual interest. Before deciding to share Mixing Center (MC), Ramp, and or a Rail Carrier(s), the following questions need to be clearly identified and resolved:

- Are the competing companies dealership located close to the consolidated and transshipping consolidation centers and ramps? If yes, are the capacities of the Mixing Centers (MC) and or the Ramps underutilized?
- Are there cost advantages to share Mixing Centers (MC) and Ramps with the competing companies?
- Are the Mixing Centers (MC) and Ramps of the competing companies' Rail Road network connected? If yes, is it feasible to us same service provider?



** Mixing Centers (MC) are also referd as Consolidation Centers*

Figure 2.4: Framework for Outbound Logistics System Collaboration in the Automotive Industry

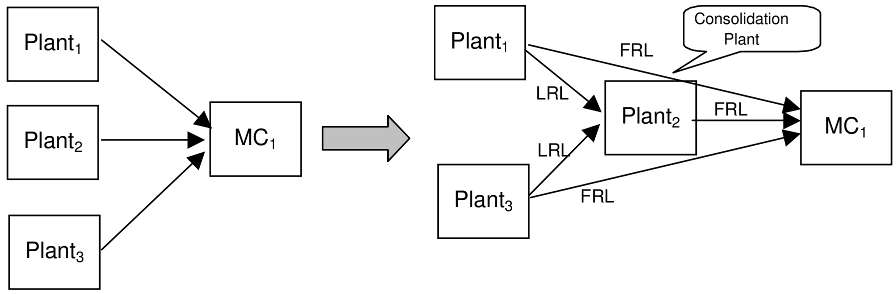


Figure 2.5: Shipment Consolidation

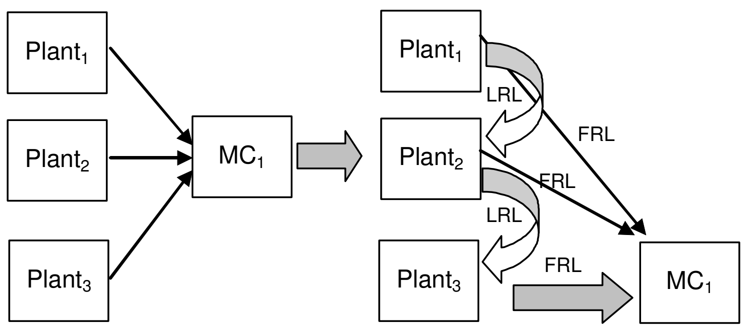


Figure 2.6: Freight Consolidation

Under the tactical level collaboration, the competing companies will share the fixed and operating cost of the underutilized Mixing Centers (MC) and Ramps proportionately. When same carriers are used to distribute vehicles then the collaborating companies will have the opportunity to re-negotiate the unit transportation cost with the carrier company. Distributing vehicles in the same locomotive train will enable the US automakers to better utilize the carrier and improve rail car shortage.

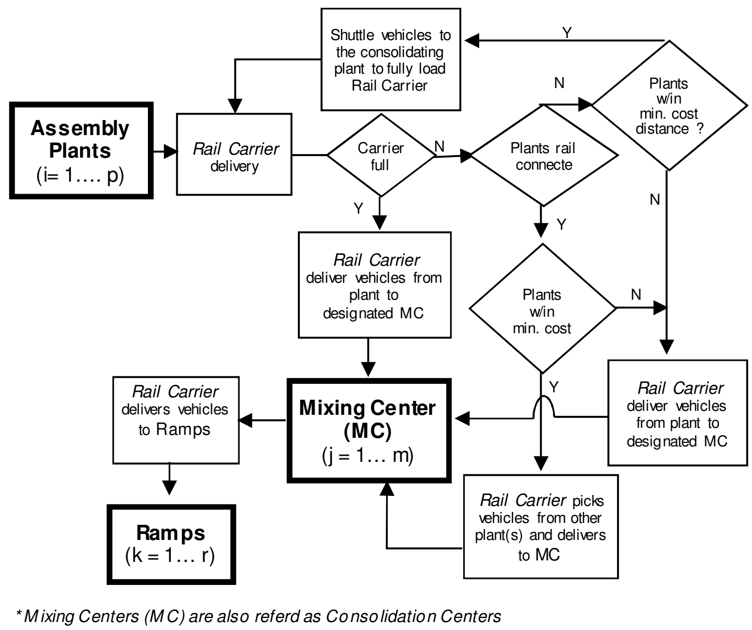


Figure 2.7: Operational Level Collaboration Process Flow

2.5.2.2 Proposed Solution

Our target in the tactical level collaboration is to better utilize the existing Mixing Centers (MC), Ramps, and the outbound logistics network resources such as labor and equipment. The tactical level collaboration is a Network Flow Planning (NFP) problem. We will assume all Mixing Centers (MC) and Ramps have infinite capacity. We will use capacitated linear optimization model to solve this problem with a given set of constraints from the real world outbound logistics network.

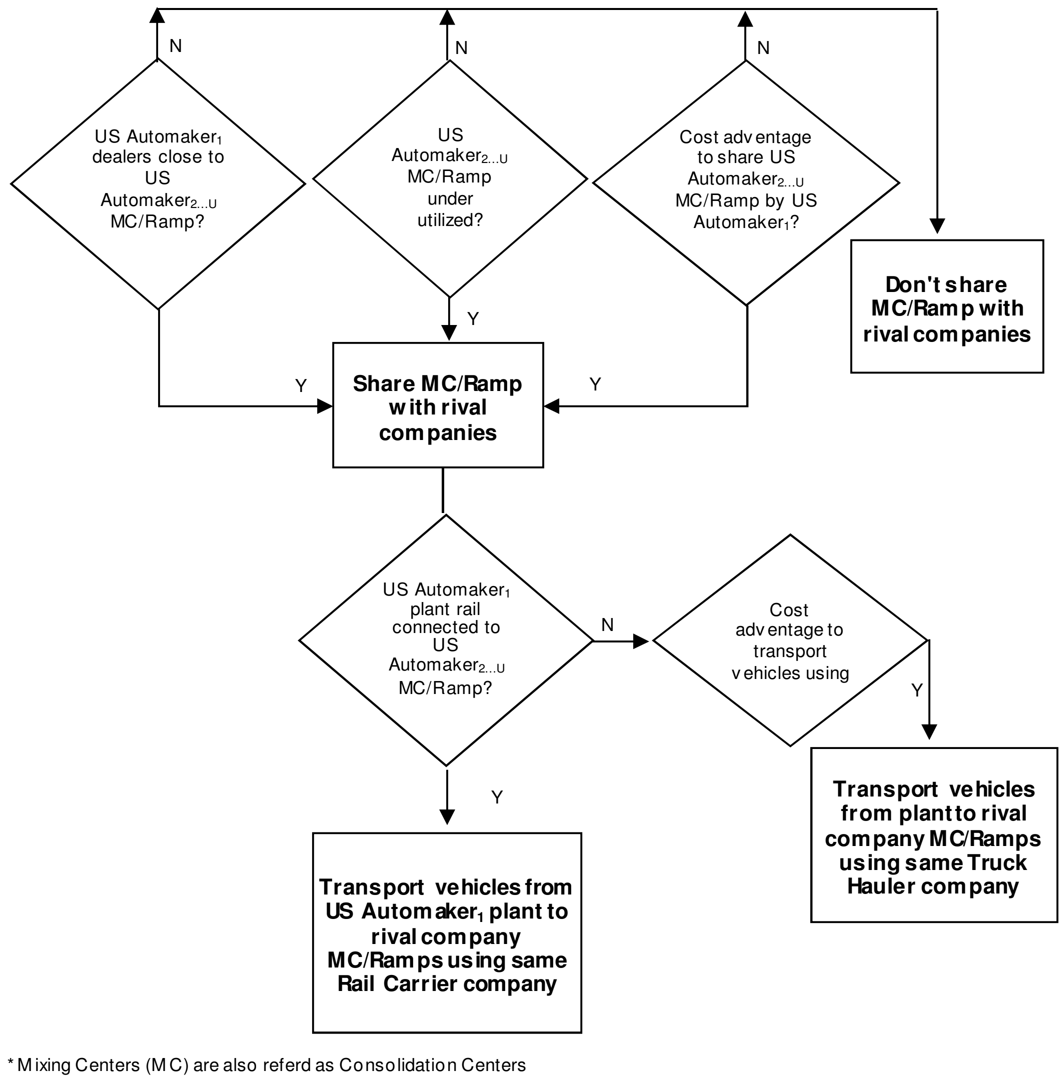


Figure 2.8: Tactical Level Collaboration Process Flow

2.5.3 Strategic Level Collaboration

For strategic level collaboration, the competing automotive companies will invest on building or leasing new Mixing Centers (MC). It is very critical to make right decisionsfor the right location to build new Mixing Centers. The inevitable questions for such decision-making problems are:

- How many Mixing Centers (MC) are needed for Collaboration?
- Where the collaborative Mixing Centers (MC) to be established?
- Will collaborative Mixing Centers (MC) be leased or newly built?

The main goals to establish or lease new Mixing Centers (MC) are to optimize customer satisfaction and minimize transportation, labor, equipment, and real estate cost. In the outbound logistics operation, there is always a trade-off between cost and customer services. Strategic level collaboration among competing companies improves the trade-offs since partnering companies share cost and resources.

2.5.3.1 Research Approach

We propose strategic level collaboration for the competing automotive companies to form alliance to further enhance the performance and cost of the outbound logistics operations. This is a long-term collaboration strategy. Under this strategy, the competing automotive companies will invest on joint ventures to build new facilities for Mixing Centers (MC) that serves all parties desired level interest. Strategic level collaboration may also take place by leasing facilities from the 3rd party service provider companies.

In Figure 2.10, we develop a process flow to aid the US automakers to make decisions on how to operate Mixing Centers (MC) activities jointly. The main goal for jointly operating Mixing Center (MC) is to find strategic locations close to the dealership networks. If the dealership network is not strategically located close to the jointly operating Mixing Centers (MC) then stop the location search. If there is cost advantage and a sizeable facility is available at a location then jointly lease a facility to operate Mixing Center (MC) activities at that location. If the location has cost advantage but there is no existing sizeable facility available at this location then consider building a new one. To build a new facility for collaborative Mixing Center (MC) operation, all competing companies are required to agree on investing capital based on cost and benefit assessments.

2.5.3.2 Proposed Solution

The strategic level collaboration is a facility location problem. In this paper we develop a multi-objective mathematical optimization model and solution techniques for capacitated collaborative Mixing Center (MC) location problem. Our objectives are to: i) minimize over all transportation cost and ii) maximize customer satisfaction through the improvements of inventory level and transportation time. Integrating the MCNF model developed in the operational model, we will develop the strategic inter-OEM collaboration model, which jointly optimizes *the design of logistics networks* of multiple OEMs. We will use mixed integer linear programming (MILP) formulation to describe and formulate the problem with the use of appropriate parameters, decisions variables, and constraints. We will use standard commercial algorithm called ILOG to solve the problem. Our model will help make decisions on facility location and sharing in addition to flow decisions.

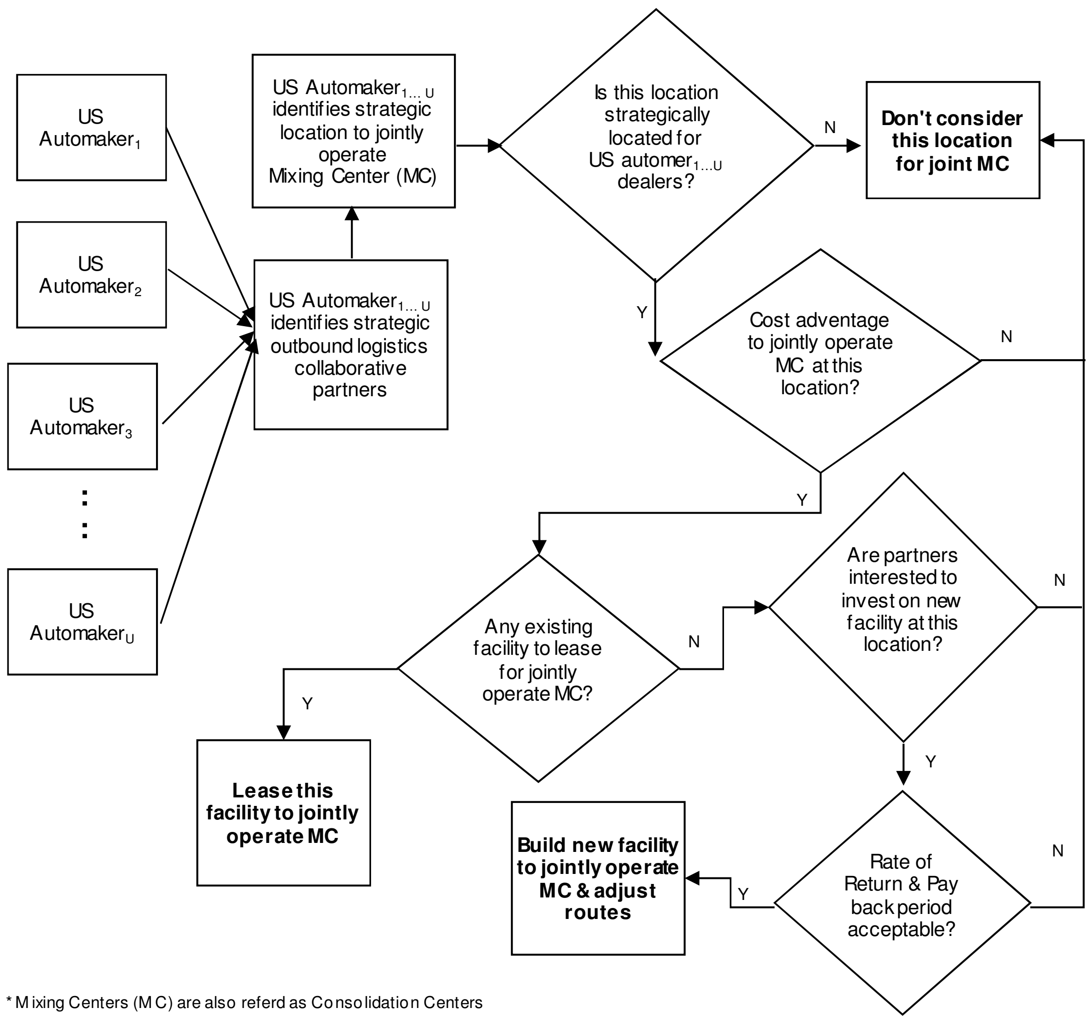


Figure 2.9: Strategic Level Collaboration Process Flow

2.5.4 Information Sharing in Outbound Logistics Collaboration

Information sharing is critical for successful collaboration in the outbound logistics operation. Robust information sharing framework need to be developed and put in place to ensure sensitive and private information on price, volume, and demographic marketing strategies are not shared among the competing companies. The design of such system will require an environment, which may be complex but will contain real time information sharing capability among collaborative companies and the 3rd party service providers.

2.5.4.1 Information Sharing Imperatives

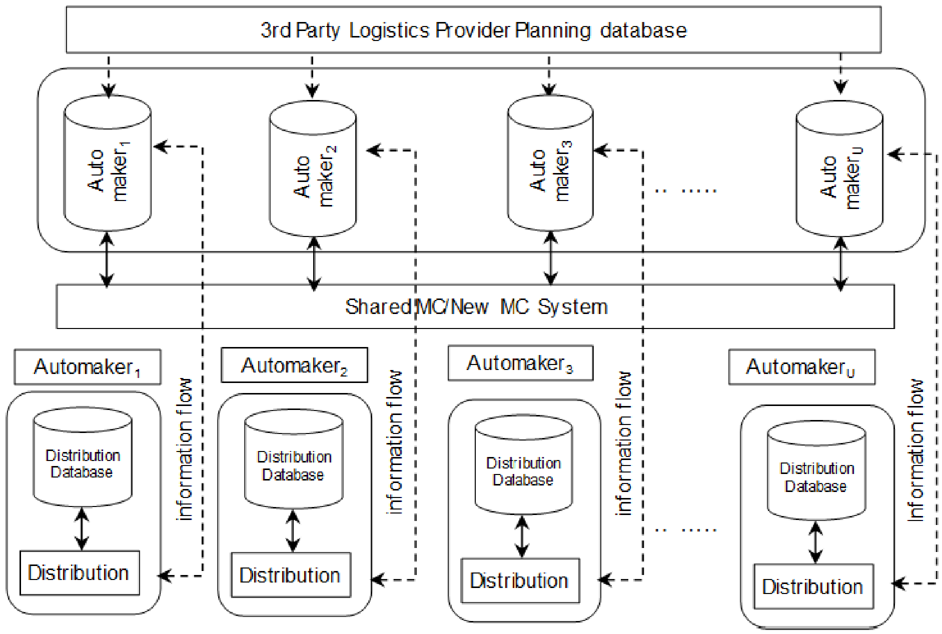
On-line shipment schedule and status visibility, consistency and accuracy of the information, the ability to make and execute real time decisions are the key essence of information sharing among the collaborative partners. The collaborative information systems need to have the following capabilities:

- To collect and share real time information on finished vehicle shipment schedule, number of finished vehicles available at the origin for shipment, rail cars availability etc. so that no locomotive train is required to wait for a desired level of loads are accumulated before departure. The locomotive train needs to receive real time information on which Assembly Plant to go to pick rail car loads to consolidate freights, if any.

- Advanced shipping information (ASI) need to be made available to the shuttle truck hauler to pick vehicles from other Assembly Plants for vehicle consolidation at the designated consolidation Assembly Plant.
- Information needs to be consistent and readily available to the key players of the outbound logistics operations. All parties need to update their information consistently so that no data are missing at a given time.
- At the operational level, the management needs to make real time decisions based on available information. For example, the management needs to know if a partially loaded carrier train is worth waiting and gets fully loaded before departure or if it is cost effective that the locomotive train departs with partial loads.

2.5.4.2 Information Sharing Framework

We develop information-sharing framework for collaborative outbound logistics operations (Figure 2.10). In the operational level collaboration, the intra company Assembly Plants will use the existing system to share real time information. The information sharing in the tactical and strategic level of collaboration will require a robust infrastructure in place so that sensitive and secret information are not leaked out to the competing companies.



Consolidation Centers are the Mixing Centers (MC)

Figure 2.10: Information Sharing Flow Process for Strategic & Tactical Collaboration

Under the collaborative information-sharing platform, each automaker will maintain its own distribution-planning database. The distribution database will feed necessary information to the 3PL service providers planning database. The 3PL service provider will maintain separate information planning database for each company. On the other hand, if the competing companies jointly manage Mixing Center (MC) then each company site management will maintain their own planning database. This way, no sensitive data will be at the hands of the competing companies and the flow of information will be maintained for the respective company only.

2.6 Conclusion

In this Chapter we developed an Outbound Logistics Collaboration framework for the competing US Automakers. We show three different levels of collaboration where the US Automakers have opportunities to gain economies of scale in transporting finished vehicles from the Assembly Plants to the Dealers via MixingCenters and Ramps.

CHATER 3

MULTI-PERIOD MULTI-PRODUCT MCNF MODEL WITH LOST SALES AND EXPEDITED SHIPPING

3.1 Introduction

We propose and develop multi-period, multi-product minimum cost outbound logistics network flow models for the US automotive companies. Our models focuses collaboration on three labels of outbound logistics operation: operational, tactical and strategic. At the operational level, we propose that the manufacturing plants and the mixing centers within the same company collaborates with each other and gain economies of scale by utilizing the resources more effectively. At the tactical level, we propose that the competing companies collaborate within their existing facilities and resources to improve system wide performance. At the strategic level, the competing companies open up new consolidation facilities and negotiate contract with the rail carrier companies to improve cost and systems performance.

In all three levels, the goal is to minimize the total distribution costs and reduce Lost Sales and Expedited shipments. We show collaboration is the way an OEM can strive to achieve the excellence in all of these three decision making levels and further improve the utilization of facilities and carrier services for economies of scale without compromising speed, quality, and customer service.

3.2 Literature Survey

There is a large body of literature on multi-period and multi-commodity network flow problems on logistics, transportation, production, inventory, and distribution systems. Multi-period and multi-product production and distribution problem was studied by Bard and Nananukul (2010), Ishii et al. (1988), Dhaenens-Flipo and Finke (2001), Dogan and Goetschalckx (1999), Geoffrion and Graves (1974), Jung et al. (2005). Eskigun*et al.* developed a large-scale capacitated (2005) and un-capacitated (2006) network design model for the outbound supply chain of an automotive company. Sourirajan*et al.* (2007, 2009) considered a distribution network design problem for a two-echelon single product supply chain. Bertazzi and Speranza (1999) presented a mixed integer linear programming (MILP) model for a multi-products logistic network system. Chopra (2003) proposed a framework for designing the supply chain distribution network.No researches to date have addressed collaboration in outbound logistics for the automotive companies.

Bard and Nananukul (2010)presented a production, inventory, distribution, and routing problem (PIDRP) as a mixed integer-programming (MIP) problem. Their model includes a single production facility serving a set of customers with a time varying demand. The capacity of the facility is limited and the planning horizon is assumed to be finite and discrete. The model assumes no shortage of products, a limited number of products can be produced in each time period, and a limited number of products can be stored at the factory and the customer sites. The objective is to minimize the total costthat includes the production setup costs, the transportation costs, and the holding costs of the product at the factory and customer sites. The authors developed a decomposition algorithm combining exact and heuristic procedures within the branch and price framework to solve the underlying MIP problem. The contribution of this research is the efficiency of heuristics and the precision of branch and price resulted in a feasible solution within a reasonable amount of time better than CPLEX or stand branch and price alone.

Ishii *et al.* (1988) considered high reliability, economic levels for the base stock, and lead times to model an integrated production, inventory, and distribution system. In this paper, a pull type ordering system called IPIDS, which integrates the production, inventory and distribution planning, and controlling functions are proposed for a 3-stage (manufacturer, wholesaler, and retailer) production and distribution network. The authors assumed that each stage of the network has sufficient capacity. The author developed basic structural formulations for minimum base stock level of new product to prevent out of stock in each stock point and the lead-time to finish the transpiration from a wholesaler to a retailer.

Dhaenens-Flipo and Finke (2001) presented an integrated multi-facility, multi-product, and multi-period model for an industrial production-distribution problem. The authors combined the production and distribution problem in the form of a capacitated network flow problem in this paper. The objective of the problem is to minimize the cost composed of production costs, production switching costs, transportation costs, and the warehouse holding costs. The authors showed that a commercial mixed integer codes like CPLEX can be used to solve a sizeable real-life industrial problem in a reasonable time; however, commercial package CPLEX will not get exact solutions for larger industrial problems in a reasonable time.

Dogan and Goetschalckx (1999) considered a multi-period production-distribution system with deterministic customer demand. The authors decomposed the production-distribution network design problem into two sub-problems: first, the strategic resource sizing and production allocation problem and second, multi-commodity network flow problem. They developed a mixed integer programming formulation based on primal (benders) decomposition integrating the strategic decisions on facilities and production lines with the tactical decisions on production, inventory, and customer allocation to minimize the supply, production, transportation, inventory, and facility cost.

Geoffrion and Graves (1974)presented an MILP model for a multi-product single period production-distribution system. The production-distribution systems considered in this model consist of several manufacturing plants with known capacities. The products are distributed through a set of distribution centers to a number of customer zones with known demand. The locations of opening distribution centers are also known. The objective function includes fixed and linear variable cost for the distribution centers, production cost, and the liner transportation cost. The model incorporates a single sourcing constraint i.e. each customer zones is assigned exclusively to a distribution center. Other constraints in the model are the plant capacity constraint, the customer demand satisfaction constraint, the upper and lower capacity constraint of a distribution center, and the logical constrains. The contribution of the authors is the development of the solution technique based on Benders decomposition to solve the MILP problem. The authors partitioned the problem into master problem and sub-problem. The master problem works with the integer variables that defines the network while the sub-problem works with the continuous variables representing the actual flow of the products obtained in the master problem. The master and the sub-problem are solved iteratively to find a sufficiently close upper and the lower bounds.

Jung *et al.* (2005) proposed a decentralized production-distribution coordinating model for third party logistics partnership. The authors assumed that there are no inventory capacity constraint at the production facilities and the distribution centers. The authors developed two linear programming models: one for the production planning problem and the other is for the distribution-planning problem. The objective function of the production-planning problem is to minimize total cost including production, inventory holding, and penalty cost for production shortage at the production facilities. The objective of the distribution planning problem is to minimize total cost including transportation cost, inventory holding cost at the distribution centers, and the lost sales penalty cost by the distribution centers. The authors developed a coordinating model, which terminates coordination once the production agent without any shortage meets the supply requirements of the distribution agent.

Eskigun*et al.* developed a large-scale capacitated (2005) and un-capacitated (2006) network design model for the outbound supply chain of an automotive company. The objectives of the models are to minimize the sum of transportation, facility and lead-time-related costs. In the models, the authors considered transportation mode selection and the relationship between lead times and the volume of flow through the nodes of the network. The lead-time is modeled as a function of node(s) dwell time and transportation time between nodes. The dwell time is the sum of the total load make-up time plus the time loss due to congestion at the respective nodes. The dwell time approximation formula presented in the papers depends on two constant values estimated from the historic dwell time data and the total number of vehicles sent to a specific destination over the planning period. The authors formulated the problem as a nonlinear 0-1-integer program model first and then reformulate it to obtain a linear integer model introducing new binary variables and constraints. A Lagrangian heuristic developed to obtain near-optimal results in a reasonable time. In our paper, we introduce an alternatives measure of the lead-times with the pipeline and in-house inventories.

Sourirajan*et al.* (2007) considered a distribution network design problem for a two-echelon single product supply chain. In this paper, the authors integrated fixed facility location, lead times and service levels into a location-allocation model in designing the distribution networks. The objective of the research was to locate the Distribution Centers (DC's) at certain locations to serve groups of retailers for minimizing the sum of the facility location cost, pipeline inventory cost, and the safety stock cost. In this paper, the authors explicitly modeled the replenishment lead-time and the service level at the DC assuming that the DC has limited capacity and hold enough safety stock to guarantee a desired service level for the retailer(s). A Lagrangian heuristic is developed to obtain a near-optimal solution in a reasonable computational time for large problem instance.

Sourirajan*at el.* (2009)proposed a genetic algorithm for a single product network design (SPNDLS) problem. The authors considered lead-time and safety stock in designing the SPNDLS model. The lead-time used in this model were inspired by the work were motivated by the work by Eskigum (2005). Like Eskigum, the authors developed a replenishment lead-time approximation formula for calculating the lead-times.

Bertazzi and Speranza (1999) presented a mixed integer linear programming (MILP) model for a multi-products logistic network system. The authors considered the network for a set of products shipped from a common origin to a common destination through one or several intermediate nodes at a given constant rate. The authors assumed that the ship frequencies are known, no stock-out during the time horizon, and the inventory cost are different for each product at each node. The authors presented two compact formulations of the MILP problem: one aggregating the inventory over time and the other aggregating the inventory over nodes. The authors developed a heuristic algorithm to solve the problem.

Chopra (2003) proposed a framework for designing the supply chain distribution network. The author described factors that influence the choice of distribution networks and the relative strengths and weakness of different types of networks.

Gendron*et al.* (1997) presented comprehensive survey of models and algorithms for capacitated network design problems. These capacitated network models have modeling and algorithmic challenges to solve. The authors developed and compared several relaxation methods fixed-charged capacitated network design problem. The proposed fixed-charge model includes flow variables for routing decisions on each arc and each commodity and integer design variables for the number of facilities to be installed on each arc. A general arc-based model was presented; interesting alternative formulations were discussed; and the existing solution approaches in the literature were outlined in this paper. The authors concluded that judicious combination of cutting planes, Lagrangean relaxation methods, and sophisticated heuristic are required to solve efficiently difficult problem like capacitated network design problems.

Hindi and Basta (1994) presented a multi-product two-stage distribution-planning problem with a number of plants, a number of intermediate warehouse, and customer's zone. The authors assumed that the demand of each customer zone for each commodity is known and that there is a limit on the warehouse capacity. The objective is to minimize total cost comprised of transportation cost, warehouse operating cost, and fixed cost of opening new warehouse. The authors formulated the problem as mixed-integer programming problem and used branch and bound method to solve it.

Miranda and Garrido (2004) proposed a non-linear mixed integer model integrating inventory control and facility location decisions for the distribution network design problem. The authors assumed that the demand for the network is stochastic and the inventory revision policy is continuous and a (Q_i, RP_i) type. The authors also assumed that each retailer is served by exactly by one warehouse, where as each distribution/consolidation center serves multiple customer zones in our model. The authors developed a heuristic based on Lagrangian relaxation and sub-gradient methods to solve the problem.

Nozick and Turnquist (2001) presented a modeling approach to the location of distribution centers integrating facility costs, inventory costs, transportation costs, and service responsiveness for the distribution of finished vehicles by an automotive manufacturer. The authors assumed continuous inventory reviews with one-for-one replacement in their model.

Tadei*et al.* (2002) considered loading, vehicle selection, and routing aspects in developing a mixed integer programming (MIP) formulation of the Auto-Carrier Transportation (ACT) problem. The authors proposed a three-step heuristic procedure to solve the problem: discomposing the problem into regional sub-problem by assigning the auto carriers to the Regions; computing a starting feasible solution for each Regional problem and then improve the initial solution using local search approach of the nonleaded vehicles.

Tsiakis*et al.* (2001) proposed a strategic planning model for a multi-product, multi-echelon supply chain networks under demand uncertainty. The authors modeled the system as a mixed integer linear programming optimization problem integrating production, facility location, transportation, and distribution and solved the problem using the Branch-and-bound techniques.

Gendron and Semet (2009) considered a two-echelon capacitated location distribution problem for a fast delivery service. The authors developed and compared arc-based and path-based mixed integer programming (MIP) formulations for the said problem. The authors showed that a LP relaxation of the path-based model provides better bound than the arc-based model. However, both models always provide the same bound when binary relaxation is used except the path-based model appears preferable over the arc-based model in terms of computational complexity. The objective of the problem is to minimize the total operating and transportation cost of the network.

Hinojosa *et al.* (2000) modeled a multi-commodity, multi-period, tow-echelon capacitated facility location problem. The objective is to minimize total transportation and operating cost of facilities open at a designated location at a given time period. The authors used Lagrangean relaxation method to obtain lower bounds of the problem, first. Then the authors used heuristic procedure to construct feasible solutions starting with the solutions obtained from the original problem.

Hinojosa *et al.* (2008) proposed a formulation for a dynamic two-echelon multi-commodity capacitated facility location problem. In this paper the authors considered the impact of building new facilities or closing down existing facilities in order to minimize total costs of transportation, inventory holding, and fixed and operating cost of facilities. The problem is modeled as mixed-integer linear programming model. A Lagrangian relaxation is employed to obtain a lower bound on the optimal objective value of the original problem. The authors then constructed a heuristic solution based on the solution of the relaxed problem.

Jaruphongsa*et al.* (2004) proposed a single product two-echelon dynamic lot-sizing model. The authors considered delivery time windows, early shipment penalties, and warehouse capacity constraints in this model. The authors assumed that the demand is known ahead of time and the demand is delivered by more than one dispatch and also no backlogging is allowed in this model. The objective of the model is to find an integrated replenishment policy to satisfy all demands at the distribution center that minimizes the total cost including the replenishing and dispatching fixed cost, unit procurement cost, unit holding cost, and the pre-shipping penalty cost. A dynamic programming based on polynomial time algorithm is proposed for computing the solutions of the problem with having $O(T^3)$ computational complexity.

Melo*et al.* (2005) proposed a mixed integer linear programming (MILP) model for the dynamic facility location problem for a multi-commodity, multi-echelon supply chain network. The authors focused on the modeling aspect of the problem than the algorithmic aspects. The authors considered many practical aspects of network design problem such as dynamic planning horizon, production, inventory and distribution planning and limitation of capacities and capital etc. The authors discovered useful insights on network design problem analyzing scenarios such as demand fluctuation, capacity expansion and reduction, and capacity shifts in this paper.

O'Kelly and Bryan (1998) developed a cost function based on flows for the hub location model. In this papers, the authors developed a piecewise linear approximation of a non-linear cost function and substitute it for the non-linear cost curve to solve the hub location model to optimality using linear programming techniques.

Pirkul and Jayaraman (1996) considered a multi-product capacitated plant and warehouse location problem for a tri-echelon system. The proposed model is a single-source model in which the customers receive multiple products from only one open warehouse. The authors presented a mixed integer-programming model for the problem. The objective of the model is to minimize the sum of the variable cost of transporting units of products from plants to the warehouses, the variable cost for distributing multiple products from warehouses to the customers, and the fixed cost of establishing and operating the plants and warehouses. The authors employed Lagrangian relaxation methods and presented a heuristics procedure for effective feasible solutions for the problem.

Pikul and Jayaraman (1998) presented a mixed integer programming formulation for a multi-commodity and multi-plant capacitated facility location problem. This is an extension of the previous model proposed by the authors (1996). The proposed model is multi-source model in which the customers receive multiple products from open warehouses. The authors presented a mixed integer programming formulations to locate a number of capacitated production and distribution centers that minimizes the total operating costs for the distribution network. The total cost of the distribution network includes the variables transportation cost between facilities and the fixed cost for opening and operating new plants and warehouses. The authors proposed an efficient heuristic solution procedure based on Lagrangian relaxation to solve this problem.

Javid and Azad (2009) designed a stochastic distribution network system integrating location-allocation problem, vehicle routing problem, and inventory control problem into one problem. The authors assumed that the distribution centers keep certain amount of safety stock in the network. The authors modeled the network as a mixed integer convex programming model and established a heuristic method using hybridization of Tabu Search and Simulated Annealing. The proposed method produced considerably efficient and effective results for a broad range of problem sizes.

Racunica and Wynter (2005) proposed a non-linear mixed integer model for an incapacitated hub location problem. The objective of the model is to minimize a linear combination of hub development cost and the cost of freight consolidation and their scale economies between hubs and hub to the destination. The authors proposed two heuristics to solve a piecewise approximation of the non-linear concave cost curves quickly even for very large problems.

Wesolowsky and Truscott (1975) developed a multi-period location allocation problem with relocation of facilities. The authors modeled a small distribution network comprising a set of facilities with known demand using mixed-integer programming techniques, first. Then they used dynamic programming techniques for the multi-period analysis of the network.

Conway and Gorman (2006) developed a simulation based iterative methodology to show a direct interdependence between level of consolidation and lot size choice for a major automotive distribution network. The authors assumed that the consolidation points are known and the network consist of numerous, heterogeneous origins and destinations requiring different optimal lot size and consolidation strategy. The authors developed a heuristic model for choosing the combination of consolidation points and lot size choice for all origins and destinations in the network that reduces the overall network transit time without compromising customer service.

Hall (1987) identified three consolidation strategies: inventory, vehicle, and terminals. He described the trade-offs between the transportation cost and the consolidation penalty costs such as inventory, longer vehicle routing, and terminal operating costs. He developed a mathematical model to examine the impact of the decision variables for each strategy.

Higginsosn and Bookbinder (1994) examined a special class of shipment-release policies for shipment consolidation. The authors considered elapsed time and accumulated quantity in their analysis and used discrete event simulation model to compare three shipment release policies: time policy, quantity policy, and time/quantity policy. The simulation result shows that the selection of consolidation policy is a function of cost and customer services directly impacted by the Management objectives.

Melachrinoudis and Min (2007) developed a mixed-integer linear programming model for the warehouse consolidation problem (WCP) to reduce transportation, inventory, and warehousing costs due to economies of scale. The authors assumed that the warehouses are company owned and that the capacity is reallocated when warehouses consolidated. The also assumed that there are no changes in customer demand and transportation infrastructure. In our research, we assume that third-party logistics providers own the warehouses and customer demand changes in each time period of the planning horizon. The authors ran sensitivity analysis on time limit and other model parameters and discovered interesting insights of the dynamics WCR. The objective of the model is to minimize total supply chain costs including production, transportation, warehousing, and warehouse relocation costs.

Pooley and Stenger (1992) used simulation modeling to study the effect of freight consolidation for a logistics system. Tyan et al. (2003) developed mathematical programming models for freight consolidation at an integrated global logistics company. A collaborative consolidation policy is recommended as a result of the cost savings and service level improvements.

Syam (2002) proposed an integrated location-consolidation model for a multi-commodity, multi-location logistics problem. The author proposed two competing methods: the simulation annealing and Lagrangian relaxation in solving the problem. The Lagrangian methods provides tight bounds and outperform the annealing procedure for medium and large size problems, whereas, the annealing procedures provides better solution than the Lagrangian methods.

The bodies of literature on location of distribution centers, production and distribution routing, design of supply chain networks have addressed various situations dealing with different models and assumptions. They addressed some characteristics of the multi-commodity, multi-periods, and multi-echelon network flow problem settings. The aforementioned literature has some common aspects with the problem studied in this paper, but doesn't address all its characteristics as mentioned in the problem definition and assumptions. In this paper, we develop a three-echelon (plant, mixing center, and ramp) outbound logistics distribution networks model for the US automotive companies. Our multi-echelon, multi-product, and multi-period OLRN (Outbound Logistics Rail Network) model combines many aspects and features previously considered in the outbound distribution systems which, in the best of our knowledge, have never been addressed all together.

As far as cost minimization is concerned, some of these papers have looked at the total logistics costs as combination of the inventory, transportation, and facility costs. But none of them considered cost of lost sales and the cost of expedited shipments as part of the total logistics cost. In fact, we are the first to incorporate the lost cost and the expedited cost as a part of the total logistics costs.

These models are not satisfactory for dealing with the need of practical vehicle OLRN for following reasons:

- When periods are defined as units of time the model complexity (e.g. number of decision variables) becomes intractable.
- When periods are defined as units of time, then the demand estimation would have to be made on a unit time basis which will increase the

variability and inaccuracy of the estimates as a result the problem solution would not be robust. By aggregating times into period, we can reduce the estimation error and hence the solutions are more robust.

- The existing formulations can be used to define the periods as in our formulation. However, they don't account for the congestion and the inventory costs in their formulations.

- The multi-source model, different plants supplying products to the different distribution centers and to the different customer zones (ramps).

The models we present in this paper will address many practical issues of the outbound logistics rail network (OLRN) system. These include a multi-period planning horizon, logistic activities such as inventory and distribution in addition to the existing network structure, capacity, and routing constraints. Our research focuses on modeling rather than algorithmic aspects.

Research Taxonomy				Hassan (Deterministic) 2010	Eskigun, Uzsoy, Preckel, Beaujon,Krishnan, Tew	Eskigun, Uzsoy, Preckel, Beaujon,Krishnan, Tew	Sourirajan, Ozsen, and Uzsoy 2007	Bard and Nananukul 2010	Bertazzi and Speranza 1999	Brown, Graves, and Honczarenko 1987	Conway and Gorman 2006	Crainic, Dejax, and Delorme 1989	Dhaenens-Flipo and Finke 2001	Dogan and Goetschackx 1999	Geoffrion and Graves 1974	Gendron, Crainic, and Frangioni 1997	Gendron and Semet- 2009	Hill and Johansen 2006	Hindi and Basta 1994	Hinojosa et. al 2000
Network Characteristics	Number of Echelons			3	3	3	2			2	2	2	3		2	3	3	1	2	2
	Planning Period	Single-period			x	x	x			x		x			x	x	x	x	x	
		Multi-period		x				x	x				x	x						x
	Planning Horizon	Finite and discrete (Static)		x	x	x	x	x	x	x		x	x				x	x	x	
		Infinite (Dynamic)																		x
	Planning Scope	Operational		x	x	x	x	x	x	x			x		x		x	x		
		Tactical		x										x						
		Strategic		x							x	x				x			x	x
	Product	Single-product			x	x	x	x										x		
		Multi-product		x					x	x		x	x	x	x	x	x		x	x
	Demand	Deterministic		x	x	x				x		x	x	x	x	x		x	x	
		Stochastic- Stationary					x										x			x
		Stochastic -Non-stationary						x												
	Transportation	Single mode		x				x		x				x			x		x	
		Multi-modal			x	x						x								
	Capacity	Capacitated		x	x		x	x		x				x	x	x	x		x	
		Un-capacitated				x														
		Capacity reduction/expansion																		
	Inventory Control Characteristics	Single (S)-/Multi-Echelon (M)		M																
		Deterministic (D) /Stochastic (S)		D														D		
		Review Policy	Continuous															x		
			Periodic	x																
		Lost Sales		x														x		
		Backorders		x														x		
		Replenishment/ Demand	Batch	x																
			Single																	
		Fixed Cost	Control	x														x		
			Global	x																
Model Type	LP/ILP - Integer Linear Programing											x								
	MILP - Mixed Integer Linear Programing			x					x	x					x					x
	MIP - Mixed Integer Program							x						x			x		x	
	NLIP - Non-Linear Integer Program				x	x														
	NLMIP - Non-Linear Mixed Integer Program							x												
	MICP - Mixed Integer Convex Programing																			
	NP-hard/Np-Complete			x											x					
	Fixed Charged Model																			
Solution Method	LP Relaxation															x	x			
	Lagrangian Relaxation				x	x										x				x
	Heuristic								x											
	Simplex Method																			
	Bender's (B), Primal (P) Decomposition									P				B	B				B	
	Dynamic (D)/Fuzzy (F) Programing																			
	Branch and Bound			x																
	Stochastic Programming- SAA			x																
	Genetic Algorithm						x													
	Scenario Planning /Iterations										x									
Variable Cost	Transportation cost			x	x	x		x	x	x		x		x	x	x	x		x	x
	Relocation/consolidation cost			x																
	Pipeline Inventory cost			x			x							x						
	Facility Inventory Holding/safety stock			x			x	x	x					x						x
	Facility operating cost									x				x					x	x
	Material Handling cost																			
	Back ordering cost			x																
	Production/mfg. cost							x		x				x						
	Lead Time Cost				x	x														
	Supply Cost													x						
	Stock-out Penalty Cost			x																
Fixed Cost	Facility Opening/Closing Cost			x	x	x	x					x		x	x	x	x		x	x
	Per shipment Cost charged by Carrier			x																
	Transportation Link/Arc Cost			x																
Objective Function	Single	Minimize Cost		x	x	x	x			x		x		x	x	x		x	x	x
		Maximize Profit																		
		Optimize Service Level																		
	Multiple	Minimize Cost																		
		Maximize Profit																		
		Optimize Service level																		

Table 3.1a: Research Taxonomy

Research Taxonomy				Hinojosa et. al 2008	Ishii, Takahashi, Muramatsu 1988	Javid and Azad 2009	Jung, Chen, and Jeong 2005	Jaruphongsa, Cetinkaya, Lee 2004	Liang 2008	Lodree Jr. 2007	Miranda and Garrido 2004	Melachrinoudis and Min 2007	Melo, Nickel, and Gama 2005	Nozick and Turnquist 2001	Pirkul and Jayaraman 1996	Pirkul and Jayaraman 1998	Syam 2002	Tsiakis, Shah, and Pantelides 2001	Topaloglu and Powell 2006	Tyan, Wang, and Du 2003	Wesolowski and Truscott 1975
Network Characteristics	Number of Echelons			2	3	1	2	2		1	1	2	2	1	2	2		3	2		
	Planning Period	Single-period				x				x		1		x	x	x	x	x		x	
		Multi-period		x	x		x	x	x		x		x						x		x
	Planning Horizon	Finite and discrete (Static)				x	x	x	x	x	x	1		x			x	x		x	x
		Infinite (Dynamic)		x									x						x		
	Planning Scope	Operational			x		x	x	x	x	x			x		x			x	x	
		Tactical										x					x				x
		Strategic		x		x							x		x			x			
	Product	Single-product				x		x		x	x	x									
		Multi-product		x	x		x		x				x		x	x	x	x	x		
	Demand	Deterministic							x		x	x		x	x	x	x	x		x	
		Stochastic- Stationary		x	x		x														
		Stochastic -Non-stationary				x		x		x			x						x		
	Transportation	Single mode				x			x		x	x	x			x	x	x	x		
		Multi-modal																		x	
	Capacity	Capacitated			x	x	x	x	x		x	x	x		x	x	x	x	x	x	
		Un-capacitated																			
		Capacity reduction/expansion											x								
	Inventory Control Characteristics	Single (S)-/Multi-Echelon (M)				S	M				S		M								
		Deterministic (D) /Stochastic (S)								S	D		S								
		Review Policy	Continuous											x							
			Periodic																		
		Lost Sales								x											
		Backorders							x	x				x							
		Replenishment/ Demand	Batch								x										
			Single											x							
		Fixed Cost	Control							x											
			Global																		
Model Type	LP/ILP - Integer Linear Programing						x		x											x	
	MILP - Mixed Integer Linear Programing			x														x			
	MIP - Mixed Integer Program					x						x	x			x					x
	NLIP - Non-Linear Integer Program																				
	NLMIP - Non-Linear Mixed Integer Program					x					x		x								
	MICP - Mixed Integer Convex Programing																				
	NP-hard/Np-Complete							x			x				x		x	x			
	Fixed Charged Model																				
Solution Method	LP Relaxation													x							
	Lagrangian Relaxation			x							x			x		x	x				
	Heuristic					x								x							
	Simplex Method																				
	Bender's (B), Primal (P) Decomposition																				
	Dynamic (D)/Fuzzy (F) Programing							D	F										D		
	Branch and Bound																				
	Stochastic Programming- SAA																				
	Genetic Algorithm																				
	Scenario Planning /Iterations						x											x			
Variable Cost	Transportation cost			x		x		x	x		x	x	x	x	x	x	x	x	x	x	
	Relocation/consolidation cost						x			x		x								x	x
	Pipeline Inventory cost																				
	Facility Inventory Holding/safety stock			x		x	x	x	x	x	x	x		x						x	
	Facility operating cost			x																	
	Material Handling cost																x	x		x	
	Back ordering cost								x	x	x										
	Production/mfg. cost						x		x			x					x	x			
	Lead Time Cost																				
	Supply Cost																				
	Stock-out Penalty Cost						x			x										x	
Fixed Cost	Facility Opening/Closing Cost			x		x					x		x	x	x	x		x			x
	Per shipment Cost charged by Carrier					x		x													
	Transportation Link/Arc Cost					x															
Objective Function	Single	Minimize Cost		x		x	x	x	x	x	x	x	x		x	x	x	x		x	x
		Maximize Profit																			
		Optimize Service Level																		x	
	Multiple	Minimize Cost												x							
		Maximize Profit																	x		
		Optimize Service level												x							

Table 3.1b: Research Taxonomy

3.3 Ship Frequency based Inventory Model

Ship frequency is defined as the number of shipments made in a given time period. The Shipment schedule is made based on ship frequency decisions. In the automotive industry, the Rail Carrier companies are required to transport finished vehicles from origin to destination on a predetermined fixed schedule.There are usually three types of ship schedule per week: daily, 3 times per week (e.g. Monday, Wednesday, and Friday), 2 times per week (e.g. Tuesday and Thursday). Any shipments outside the predetermined set schedules are called premium or expedited shipments. The expedited shipments are made on emergency basis and are very costly.

3.3.1 Definition of Timeline

We define the planning horizon as T, the time period as $t \in T$, and the time unit as $l \in t$. The planning horizon is equivalent to a year, time period is equivalent to a month, and the time period is equivalent to a day. The sum of all time units in a period t is also defined as L (Figure 3.1).

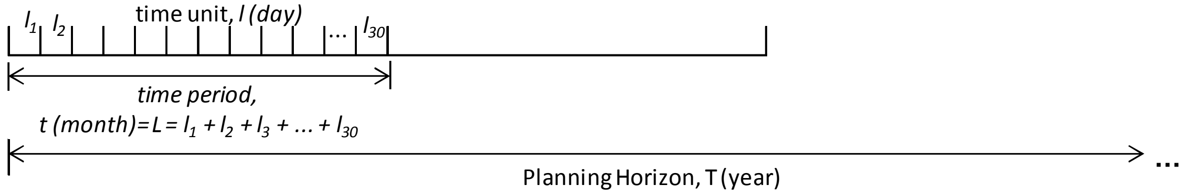


Figure 3.1: Timeline

3.3.2 Ship-frequency based Average Inventory

In this section, we present an alternative method to approximate the average inventory level at a given time period. The average inventory level is a function of the beginning inventory level, the ship frequencies (number of shipments per time period) and the inbound and outbound shipment sizes.We assume:

1. Inbound and outbound shipments are equally spaced.
2. Inbound and outbound shipments are made at the beginning of each time unit within the time period

We define,

x_{ijt}: Average number of units transported per shipment from node $i$to $j$at time period t

r_{ijt}: Ship frequency (number of shipments) from node i to j at time period t

k: Shipment identifier ($k = 1, 2, 3, \ldots r_{ijt}$)

$\mathrm{I_{it}}$:*Ending inventory at node* i*in period* t

L: *Duration of a time period (total time units)*

The time interval between two consecutive shipments is equal as per the assumption. The interval length between two consecutive shipments is L/r_{ijt}.

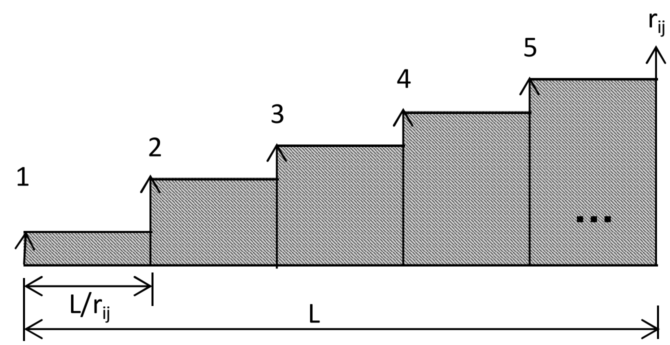


Figure 3.2: Time interval between shipments

By definition, there is one (1) shipment in the initial $1L/r_{ijt}$ time units, two (2) shipments in the initial $2L/r_{ijt}$ time units, three (3) shipments in the initial $3L/r_{ijt}$ time units and so forth. Hence, the duration-weighted sum of the number of shipments is calculated as below:

$$\frac{1L}{r_{ijt}} + \frac{2L}{r_{ijt}} + \frac{3L}{r_{ijt}} + \cdots + \frac{r_{ijt}\,L}{r_{ijt}}$$

$$= \frac{L}{r_{ijt}}\left(1 + 2 + 3 + 4 + \cdots + r_{ijt}\right) = \frac{L}{r_{ijt}}\sum_{k=1}^{r_{ijt}} K$$

$$= \frac{L}{r_{ijt}}\left[\frac{r_{ijt}\left(r_{ijt} + 1\right)}{2}\right] = \frac{r_{ijt}(r_{ijt} + 1)}{2r_{ijt}}L = \frac{r_{ijt} + 1}{2}L \qquad (1)$$

Dividing the expression in (1) by L would give us the average number of shipments at any time in the period.

$$Average\ number\ of\ shipments\ at\ any\ time\ unit\ = \frac{r_{ijt}+1}{2} \qquad (2)$$

Note that the implicit assumption in (1) is that the r_{ij} shipments are equally spaced; if this does not hold true then the above formulations are not correct. In addition the timing of the first shipment makes a difference in the result. When we multiply with the flow volume x_{ijt} in each shipment (e.g. size of shipment) $\frac{r_{ijt}+1}{2}x_{ijt}$, then we obtain the average inventory due to this shipment. Therefore, we determine the average inventory level in the period by considering initial inventory, all inflows and outflows. Specifically, the average inventory due to outflow from node $i$at any point of time in period $t$is $\sum_j \frac{r_{ijt}+1}{2}x_{ijt}$ and the total average inventory due to inflow to node i at any point of time in period $t$is$\sum_j \frac{r_{jit}+1}{2}x_{jit}$. Including the initial inventory, the average inventory at node i in time period t then become:

$$I_{it} + \sum_j \frac{r_{jit}+1}{2}x_{jit} - \sum_j \frac{r_{ijt}+1}{2}x_{ijt} \qquad (3)$$

3.3.3Non-Negativity Inventory Condition

As part of the total logistics cost, the average inventory cost is to be minimized. Since the above expression's last term is negative, we could have negative average inventory. Note that while we assume that each node has positive inventory at the beginning and end of each time period, this does not guarantee the non-negativity of the average inventory. As a result, the optimization result would favor such solutions where the average inventory is negative. The condition for having non-negative average inventory over each time period is:

$$I_{it} + \sum_{i,j} \frac{r_{jit} + 1}{2} x_{jit} \geq \sum_{j,i} \frac{r_{ijt} + 1}{2} x_{ijt}$$

Following lemma proves a condition, which must hold for non-negative average inventory.

Lemma: The following condition ensures that the average inventory in a given time period t at location $i$is non-negative.

$$I_{it} + \sum_{j} x_{jit} \geq \sum_{j} x_{ijt}$$

Proof: The condition for non-negative average inventory is

$$I_{it} + \sum_j \frac{r_{jit} + 1}{2} x_{jit} - \sum_j \frac{r_{ijt} + 1}{2} x_{ijt} \geq 0$$

Furthermore we have that ending inventory of time t is non-negative

$$I_{it} + \sum_j r_{jit} x_{jit} - \sum_j r_{ijt} x_{ijt} \geq 0$$

Let's denote

$$\Delta = I_{it} + \sum_j r_{jit} x_{jit} - \sum_j r_{ijt} x_{ijt}$$

Multiplying each side of the non-negative average inventory by 2 and substituting for Δ above

$$2I_{it} + \sum_j (r_{jit} + 1) x_{jit} - \sum_j (r_{ijt} + 1) x_{ijt} \geq 0$$

$$(I_{it} + \sum_j r_{jit} x_{jit} - \sum_j r_{ijt} x_{ijt}) + (I_{it} + \sum_j x_{jit} - \sum_j x_{ijt}) \geq 0$$

$$\Delta + I_{it} + \sum_j x_{jit} - \sum_j x_{ijt} \geq 0$$

Hence, if$I_{it} + \sum_j x_{jit} - \sum_j x_{ijt} \geq 0$ and given that $\Delta \geq 0$ (due to the condition that net inflow exceeds net outflow), then the average inventory is non-negative.

□

Condition of the above lemma is *sufficient* for average inventory to be positive, but is not *necessary* as sufficiently large positive Δ can also ensure the non-negativity of average inventory.

Neither the non-negative average inventory nor the non-negative beginning or ending inventory does not guarantee the non-negativity of inventory at a time unit during the period. Our assumption is that the inventory cannot be negative at a given time unit within each time period. So, having positive inventory at the beginning and end of a time period is only a necessary condition for non-negative inventory at any period. Also it can be shown that the condition of the lemma does not guarantee the non-negativity of inventory within a period. Therefore we need to enforce it through a separate set of constraints. Otherwise, the non-negativity causes the optimization to seek shipment solutions leading negative inventory, which is infeasible.

3.4 Shipment Off-setting

We define shipment *offsetting* as the number time units the first shipment is sent (outflow) or received (inflow) from the beginning of the period.

o_{ijt}: Number of time units the first shipment is sent to node j from node i from the beginning of the time period t.

It can be shown that the offsetting is bounded from above as follow,

$$o_{ijt} \leq L - (r_{ijt} - 1)\left\lfloor \frac{L}{r_{ijt}} \right\rfloor - 1 \tag{4}$$

Where, $\lfloor L/r_{ijt} \rfloor$ is the integer number of days between shipments.

Let's consider the simple scenario where initial inventory is zero $(I_0 = 0)$ and there are 6 time units in the period. Further, there is single inflow arc of 20 units per shipment size with three shipments and single outflow of 60 units per shipment size with one shipment. Assuming inflow and outflow starts at the beginning of the time period resulting with inflow pattern of (20, 0, 20, 0, 20, 0) and outflow pattern of (60, 0, 0, 0, 0, 0) netting (-40, -40, -20, -20, 0, 0) in the stock levels.

This is an example where balancing of total inflow with total outflow cannot prevent negativity of inventory levels. However, if we time the outflow of 60 units to be at or after the last 20 units of inflow shipments, then we can ensure non-negativity of inventory. Specifically, if the outflow pattern is (0, 0, 0, 0, 60, 0) then the correspondingstock levels would be (20, 20, 40, 40, 0, 0). In other words, we need to know when to begin outflows so that the inventory levels never becomes negative at any time unit within a given time period. Clearly, the guarantee that inventory level is always non-negative necessitates postponing the outflows later than the inflows.

One way to handle this is to introduce another variable (α_{ij}), where $0 \leq \alpha_{ijt} \leq \frac{r_{ijt}+1}{2}$, which represents the offset of the outflow shipment of an arc flow within the period of time. We define the offset as the duration in time units where the first flow begins after the beginning of the period. By offsetting shipments, we are postponing them to later time in the period, which decreases the average number of shipments executed at any given time. Therefore, we redefine the average number of shipments at any point of time in a period with offset first shipment:

$$Average\ number\ of\ shipments\ at\ any\ time\ unit\ with\ offset = \frac{r_{ijt}+1}{2} - \propto_{ijt} \quad (5)$$

For instance, consider the previous example with outflow pattern of (60, 0, 0, 0, 0, 0) for which the average number of outflow shipments without offset is $\frac{(r_{ijt}+1)}{2} = \frac{1+1}{2} = 1$. Similarly, for the outflow pattern of (0, 0, 0, 0 60, 0), we have an offset of 4 time units and the average number of outflow shipments can be empirically calculated by observing that until $5th$ time units there are no shipments and in each of the last two time units there are 1 shipment. Thus the average number of shipments is $(0+0+0+0+1+1)/6 = 2/6 = 1/3$. Hence,

using the formula in (4), we can calculate $\propto_{ij}$as $\propto_{ij}= \frac{(r_{ijt}+1)}{2} - \frac{1}{3} = \frac{1+1}{2} - \frac{1}{3} = \frac{2}{3}$.
Note that the $\propto_{ijt}$ value is different than the offset duration of 4 time units.

3.4.1 Inventory level and Off-setting

While offsetting outflows can prevent the negative inventory within a period, at the same time it increases the average inventory. Similarly, offsetting the inflows would increase the risk of negative inventory while reducing the average inventory. Therefore, the offsetting of outflows and inflows counteract. The general expression of the average inventory in period t for node i with offsetting of both inflows and outflows as follows:

$$I_{it} + \sum_{j,i} (\frac{r_{jit}+1}{2} - \propto_{jit}) x_{jit} - \sum_{i,j} (\frac{r_{ijt}+1}{2} - \propto_{ijt}) x_{ijt} \qquad (6)$$

We now illustrate the interaction of the inflow and outflow offsetting as well as the impact on the average inventory and feasibility.

Example 3.1:

Consider a network with two Manufacturing Plants $(P1, P2)$, one Mixing Center(M), and one Ramp (R). Let's, assume the following problem parameters:

$$I_{0i} = 0, x_{P1,M} = 10, r_{P1,M} = 5, x_{P2,M} = 8, r_{P2,M} = 5, x_{M,R} = 20, r_{M,R} = 4$$

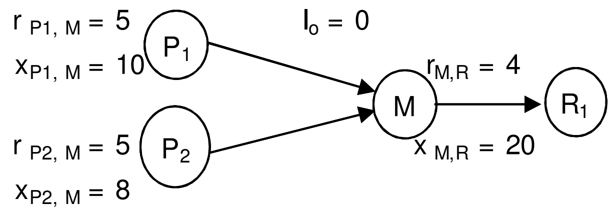


Figure 3.3: Network Flow for Example 3.1

We show the effect of different offsetting levels for $P1 - M$ inflow and the outflow in Figure 3; the other inflow offset is 0. These offsets are limited with the upper bounds given by equation (4), e.g. maximum offsets are 3 and 4 for inflow and outflow, respectively. Since not every offset combination leads to a feasible solution (e.g. non-negative inventory), we characterize the feasible and infeasible solutions with red and blue colors, respectively. While negative average inventory combinations, where (inflow, outflow) offsets are (2,0) and (3,0) are clearly infeasible, the rest of the combinations shown in blue are infeasible due to at least one occurrence of negative inventory within the period. Clearly, the offset combination with minimum average inventory is the most desirable combination. In this case, the minimum average inventory is attained by offsetting inflow by 3 and outflow by 4 time units.

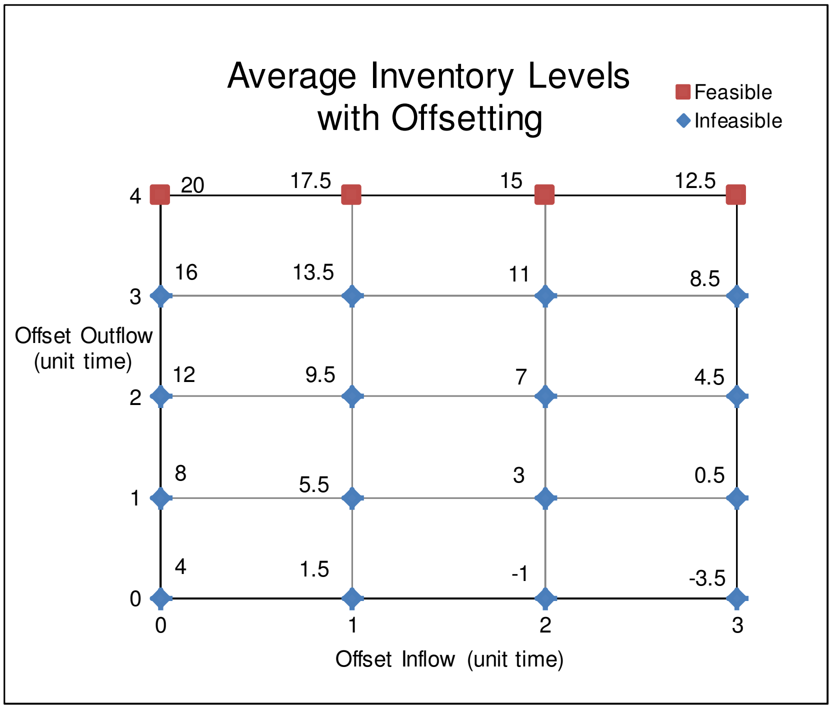


Figure 3.4: Average inventory level with different offsetting combinations for P1-M inflow and M-R1 outflow in Example 3.1.

Figure 3.4 shows that as inflow offsetting increases, the average inventory decreases linearly (e.g. at a rate of 2.5 units) and increases the likelihood of negative inventory within the period. Similarly, the outflow offsetting increases the average inventory at a linear rate (4 units for each time unit of offsetting) and increases the chance of feasible solution. For this example, the state where inventory is non-negative throughout the period is only occurring when the outflow is offset as late as possible across all inflow offset cases. This is not always the case as illustrated in example 3.2.

We demonstrate the minimum average inventory solution in Table 1 where $P1 - M$ inflow is offset by 3 time units and $M - R1$ outflow is offset by 4 time units. This is a feasible solution since there are no negative inventories at any time unit within the time period (e.g. rightmost column).

Time units *l*	Inflow		Outflow	Inflow to M	Outflow from M	Net flow per time unit	Empirical Model (inventory level)
	$r_{P1,M}$	$r_{P2,M}$	$r_{M,R}$				
1	0	8	0	8	0	8	8
2	0	0	0	0	0	0	8
3	0	0	0	0	0	0	8
4	10	0	0	10	0	10	18
5	0	8	20	8	20	-12	6
6	0	0	0	0	0	0	6
7	0	0	0	0	0	0	6
8	10	0	0	10	0	10	16
9	0	8	0	8	0	8	24
10	0	0	20	0	20	-20	4
11	0	0	0	0	0	0	4
12	10	0	0	10	0	10	14
13	0	8	0	8	0	8	22
14	0	0	0	0	0	0	22
15	0	0	20	0	20	-20	2
16	10	0	0	10	0	10	12
17	0	8	0	8	0	8	20
18	0	0	0	0	0	0	20
19	0	0	0	0	0	0	20
20	10	0	20	10	20	-10	10

Table 3.2: Inventory level with offsetting and initial inventory Zero

Example 3.2:

This example is same as the preceding example except that the initial inventory is 5 (Figure 3.5). In the previous example, the feasible offsetting combinations were attained when we offset the outflow as late as possible which did not depend on the inflow offsetting level. In this example, we demonstrate the case where the necessary outflow offsetting depends on the inflow level.

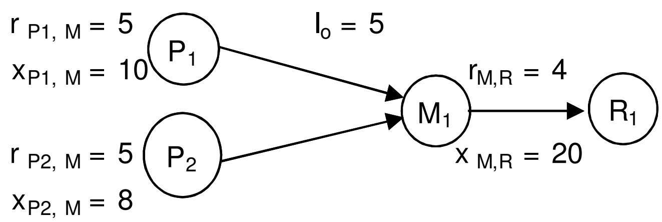


Figure 3.5: Network Flow for example 3.2

In Figure 3.6, we again show the average inventory and feasibility effect of different offsetting levels for $P1 - M$ inflow and $M - R1$ outflow. In this case, the outflow offset levels for feasible solution depends on the level of inflow, e.g., outflow offset of 3 time units is needed for inflow offset of 3 time units whereas 2 time unit outflow offset is sufficient in the remainder levels of inflow offsetting.

Among the offset combinations in Figure 3.6, the minimum average inventory is attained when both the inflow and outflow are offset by 2 time units. This example shows that the best solution is obtained by not offsetting as late as possible but by offsetting atsome intermediate level. Clearly, this combination depends on the flow parameters $(x_{ijt,}r_{ijt})$of inflows and outflows as well as the initial inventory.

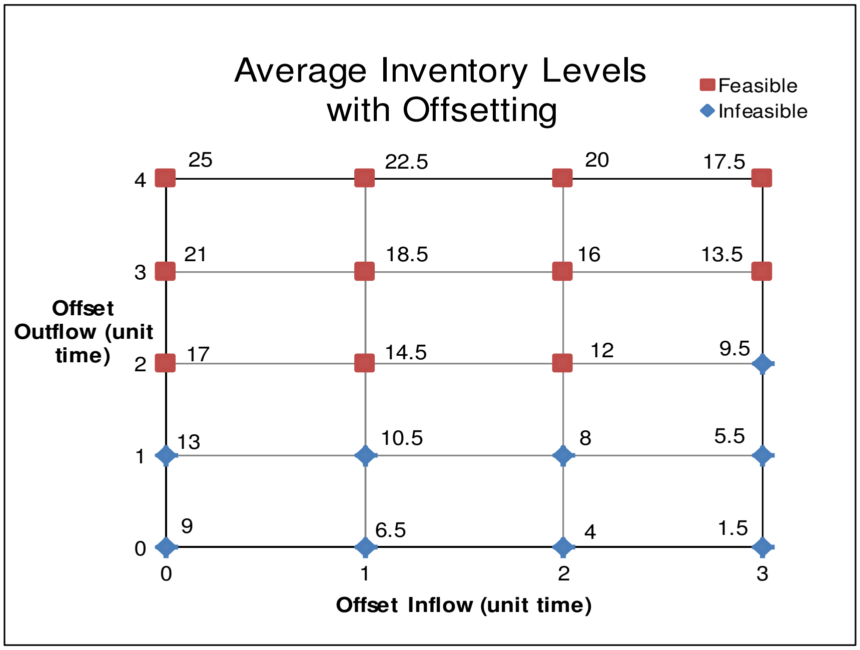


Figure 3.6: Inventory Level with off-setting and initial inventory level 5 unit

3.4.2 Inflow and outflow relationship

The destination node receives flows from many origin nodes. Hence, the outflow of an origin is not the same as inflow to the destination node. We define relationships for ship frequency and off-setting between origin and destination nodes.

The inbound ship frequency to a destination node is a function of outbound ship frequency, off-setting, and transportation time of the origin node.

$$\hat{r}_{ijt} = f(r_{ijt}, o_{ijt,}\tau_{ij})$$

Similarly, off-setting at the destination node is a function of the off-setting at the origin node and the transportation time from the origin node to the destination node.

$$\hat{o}_{ijt} = f(\, o_{ijt,} \tau_{ij})$$

Also, redefining $\propto_{ijt}$ different for inflow and outflow, we get the general expression of the average inventory in period t for node i with offsetting of both inflows and outflows as follows:

$$I_{it} + \sum_{j,i} (\frac{r_{jit} + 1}{2} - \hat{\alpha}_{jit}) x_{jit} - \sum_{i,j} (\frac{r_{ijt} + 1}{2} - \propto_{ijt}) x_{ijt} \qquad (7)$$

Where,

$\hat{\alpha}_{jit} = \frac{r_{jit}}{L} \hat{o}_{jit}$, off-setting for inflows

$\propto_{ijt} = \frac{r_{ijt}}{L} o_{ijt}$, off-setting for outflows

$$\hat{o}_{jit} = \; o_{jit} + \tau_{ji}$$

Substituting $\hat{\alpha}_{ijt}$ and $\propto_{ij}$ values in equation (7), we get the following expression for average inventory in period t for node i with offsetting of both inflows and outflows:

$$I_{it} + \sum_{j,i} (\frac{r_{jit}+1}{2} - \frac{r_{jit}}{L} \hat{o}_{jit}) x_{jit} - \sum_{i,j} (\frac{r_{ijt}+1}{2} - \frac{r_{ijt}}{L} o_{ijt}) x_{ijt} \quad (8)$$

3.4.3 Feasible Flows

As discussed above, the feasible flow solution, e.g. non-negative inventory at any time unit in a period, can be attained by properly offsetting the inflows and outflows at a node. Furthermore, there is no particular correlation between the offsetting levels of inflows and outflows necessary to ensure feasibility. Further, identifying the best offset combination is not straightforward let alone a feasible combination. Hence we define a set of variables and constraints for detecting and preventing the non-negative inventory at every time unit.

First variable we need to define is the duration between consecutive shipments on an arc (i, j)in time period t.

∂_{ijt}: Number of time units between consecutive shipments in time period t on arc (i, j)

We determine ∂_{ijt}through the following constraint and an integral requirement for ∂_{ijt}

$$\frac{L}{r_{ijt}} \geq \partial_{ijt} \geq \frac{L}{r_{ijt}} - 1 + \epsilon \quad (9)$$

where, ϵ is a very small positive number. Note that ϵ is needed for the case$mod\ (L, r_{ijt}) = 0$.Note that ∂_{jit} is identical for inflow and outflow on the same arc.

The frequency of shipment in a time period from node j to i in time t, r_{jit} is only applicable for the shipping node (e.g. outflow). Given that we have transit time τ_{ji}, then the *actualized* number of inflow shipments from node j to i is less than or equal to r_{jit}. We denote this actualized number of shipments with $\hat{r}_{jit}$.

$\hat{r}_{jit}$: Number of shipments sent from j to i in period t that arrive in t.

This can be calculated through the following constraint and an integral requirement for $\hat{r}_{jit}$:

$$\frac{L - 1 - \tau_{ji} - o_{jit}}{\partial_{jit}} + 1 \geq \hat{r}_{jit} \geq \frac{L - 1 - \tau_{ji} - o_{jit}}{\partial_{jit}} + \epsilon$$

Another variable is the number of shipments on an arc by a given time unit of a period. This is necessary for inventory calculations at specific time units.

β_{ijlt}: Number of shipments on arc (i, j) until time unit $l$in period t with offset o_{ijt}

This is found by,

$$\beta_{ijlt} = \begin{cases} \lfloor (l-1-o_{ijt})/\partial_{ijt} \rfloor + 1 & l \geq o_{ijt}+1 \\ 0 & otherwise \end{cases} \tag{10}$$

The above expression can be reformulated in the form of the following constraint together with integral β_{ijlt},

$$\frac{(l-1-o_{ijt})}{\partial_{ijt}} + 1 \geq \beta_{ijlt} \geq \frac{(l-1-o_{ijt})}{\partial_{ijt}} + \epsilon, \tag{11}$$

where, ϵ is a very small positive number.

Note that the value of β_{ijlt}applies only for outflows from node i to node j in time period t. As for the inflow to node i, not all of the shipments sent from j to i in period t will necessarily arrive within the period given that there is transit time τ_{ji}.

$\hat{\beta}_{jilt}$: Number of shipments on arc(j,i) until time unit $l$in period t with offset o_{jit}

The equivalent expression for inflow to i is therefore,

$$\frac{(l-1-o_{jit}-\tau_{ji})}{\partial_{jit}} + 1 \geq \hat{\beta}_{jilt} \geq \frac{(l-1-o_{jit}-\tau_{ji})}{\partial_{jit}} + \epsilon, \tag{12}$$

The condition that at any time unit, the inventory will be non-negative can be expressed as the following constraint.

$$I_i^{max} \geq I_{it} + \sum_j \hat{\beta}_{jilt} x_{jit} + \sum_j \left(\beta_{ji(L+l)(t-1)} - \hat{r}_{ji(t-1)}\right) x_{ji(t-1)} - \sum_j \beta_{ijlt} x_{ijt} \geq 0 \quad \forall i,t,l \tag{13}$$

Where,$I_i^{max}$is the maximum allowable inventory in location i at any time unit.

This constraint accounts for, in the order of terms, the initial inventory at time t, inflow to i sent in t arriving in t, inflow to i sent in $t-1$ arriving time unit of period t, and the outflow from i in period t. Here we state the implicit assumption that all in-transit shipments sent in the preceding time period $t-1$ arrives within the time period t. It is not a restrictive assumption and extensions can be accounted for by considering a finite number of preceding periods in the above constraint. The current assumption is that$\tau_{ji} \ll L$.

Note that since the planning horizon is finite, we do have in transit shipments in the beginning and shipments which are initiated in the last planning period but will come after the end of the horizon.

For the in-transit in the beginning of the planning horizon, we modify as

$$I_i^{max} \geq I_{i0} + \sum_j \hat{\beta}_{jil1} x_{ji1} + \sum_{l' \leq l} g_{jil'} - \sum_j \beta_{ijl1} x_{ij1} \geq 0 \quad \forall i, l$$

$g_{jil'}$: Size of the in-transit shipment sent prior to the beginning of the planning horizon from j to i and arriving at time unit l' of the initial period $t = 1$.

Note that in the beginning of the planning horizon we know $g_{jil'}$flows hence we replace $\sum_j (\beta_{ji(L+l)(t-1)} - \hat{r}_{ji(t-1)}) x_{ji(t-1)}$ with $g_{jil'}$in the general constraint for the initial period.

3.5 Lost Sales and Expedited Shipments

The lost sales are the opportunity costs of lost revenue and often resulting to a potential loss of customer goodwill and loyalty (Hillier and Lieberman, 2001). Lost sales are the hidden factories within the unmet demand of the customers. This is why, lost sales are difficult to measure and quantify. Through backorders, some unfilled demands of the customers are met in the next scheduled shipment deliveries. However, the remainder of the unmet demand is known as lost sales.

The lost sales demand are time sensitive as the customers are willing to wait until a threshold time to acquire the product of choice; customer moves to competitors any time beyond that threshold time.

3.5.1 Literature Review

There exist an extensive literatures associated with lost sales inventory models. These papers includes lost sales based on base stock policies (Johansen 2005), finite horizon lost sales inventory model with periodic review policy (Lu et al. 2006), replenishment policies for the continuous review inventory model (Hill 1999), inventory policies with Poisson demand and lost sales (Johansen and Thorstenson 1996), Optimal and near optimal policies for lost sales inventory model (Hill and Johansen 2006), inventory system with customer impatience (Benjaafar et al 2010), periodic review inventory control with lost sales (Janakiraman and Muckstadt 2004), multi-echelon models with lost sales (Hill et al. 2007), and probabilistic lost sales inventory system (Fergany and El-Wakee 2006).

Johansen (2005) studied optimal base-stock for a lost sales inventory model with a sequential supply system and Erlangian lead times. Bordley et al. (2006) showed that the expected lost sales are proportional to the standard deviation of the retailer's demand uncertainty. The authors derived relations between expected lost sales and the number of retailer outlets and showed that the consolidation of distribution channels will reduce lost sales by reducing expected inventory shortages.

Chu et al (2004) explored inventory models with a mixture of back orders and lost sales. Hill (1999) considered continuous review inventory model with replenishment policies having Poisson demand, fixed replenishment lead time, and lost sales during stock out time. Fergany and El-Wakee (2006) derived a probabilistic lost sales inventory model considering order cost as a function of the order quantity.

Mohebbi (2003) presented an analytical model for a continuous-review inventory system with compound Poisson demand and Erlang lead time distribution. In this paper, the author expanded some earlier research findings in lost-sales inventory systems with variable lead times to address the supply interruption problems.

Hill and Johansen (2006) considered policy iteration algorithm for the lost sales inventory model with only one outstanding replenishment order at a given time. The objective is to minimize the long run average cost per unit time of ordering, stock-holding and lost sales. The authors considered continuous and periodic review of the inventory policy, fixed and variable lead times, and order sizes in this model.

Lodree Jr. (2007) considered optimal stocking policies for firms with long procurement lead-time and shortages that are partially backlogged. The author assumed that the supplier initiates emergency replenishment at an expensive premium cost when there is a shortage or realizes lost sale penalties. The author developed two mathematical models: one involving mixtures of backorders and lost sales and the others with backorders, lost sales, and potentially lost contract.

In this section, we develop a Regression model for lost sales and expedited shipments based on shipment size and the frequency of shipment. The intent of the model is to give managerial insights to the dealers on potential lost sales and expedited shipments based on customer patience. The dealers will be able to assess the timing and volume of shortage of vehicle in the show room based on shipment schedule priori. To the best of our knowledge no research has been done to date on estimating lost sales and expedited shipments based on shipment size and ship frequency. In fact, we are the first one to introduce a scheduled based regression model to estimate lost sales and expedited shipments.

3.5.2 Operational Definitions

The Automotive Outbound Logistics Network, the ramps are located by automotive dealer zones. The dealers get their vehicles three (3) ways: (1) from Vehicle Assembly plants (2) from Consolidation Centers, and (3) from the Ramps. We measures Lost Sales at the dealers for those vehicles delivered from the ramps.

The customer order arrives to the dealers randomly. The dealer places the orders to the ramps daily. We assume the dealer daily demand is identically independently distributed with same mean and variance of zero. The service rate (fill rate) of the ramps to the dealer orders measures Lost Sales and Expedited Shipments.

If a customer order is placed at the dealer and the desired vehicle is not available at the show room then the dealer places a backorder of the vehicle based on customer patience time. If the backorder time is less than the customer patience time then dealer places the order on a regular shipment; if the backorder time is more than the patience but less than the expedited shipment threshold then the dealer places the order on Expedited shipment such that the vehicle arrives at the show room within the customer patience time; for any backorder time is longer than the Expedited Shipment Threshold time then the dealer won't make the backorder resulting Lost Sales as customer will not willing to wait for the order rather go to for a different make and model or to the rival company dealers. Figure 3.7 shows the schematic of Lost Sales and Expedited Shipments.

- **Backorder Time** (BT) is the number of time units in days demand to be met from day of order placed by the dealer when there is a shortage.
- **Patience Time**(PT) is the number of time units in days a customer is willing to wait for a vehicle of choice backordered by the dealer from the day of order placed.

- **Expediting Threshold** (ET) is the number of time units in days a dealer is willing to place backorder for a customer's vehicle of choice when there is a shortage in order to meet customer patience time.
- **Regular Backorder Shipments** (RBS) is the number of time units in days within which the dealer fulfills customer's vehicle of choice by placing backorders through Regular Shipments. The dealer places backorders on regular shipment if Customer Patience Time (PT) is less than the Backorder Time (BT).
- **Expedited Backorder Shipments** (EBS) is the number of time units in days within which the dealer fulfills customer's vehicle of choice by placing backorders through Expedited Shipments. The Expedited Shipments are more expensive than the Regular Shipments. The dealer places backorders on expedited shipment if Backorder Time (BT) is higher than Customer Patience Time (PT) but less than or equal to the Expedited Threshold (ET) Time.
- **Lost Sales** (LS) is depends on the service rate. The lower the service rate the higher the Lost Sales are probability is. If Backorder Time (BT) is higher than the Expedited Threshold (ET) Time the dealer will not be able to get customer's vehicle of choice delivered to the show room within Patience Time (PT) resulting in a Lost Sales.

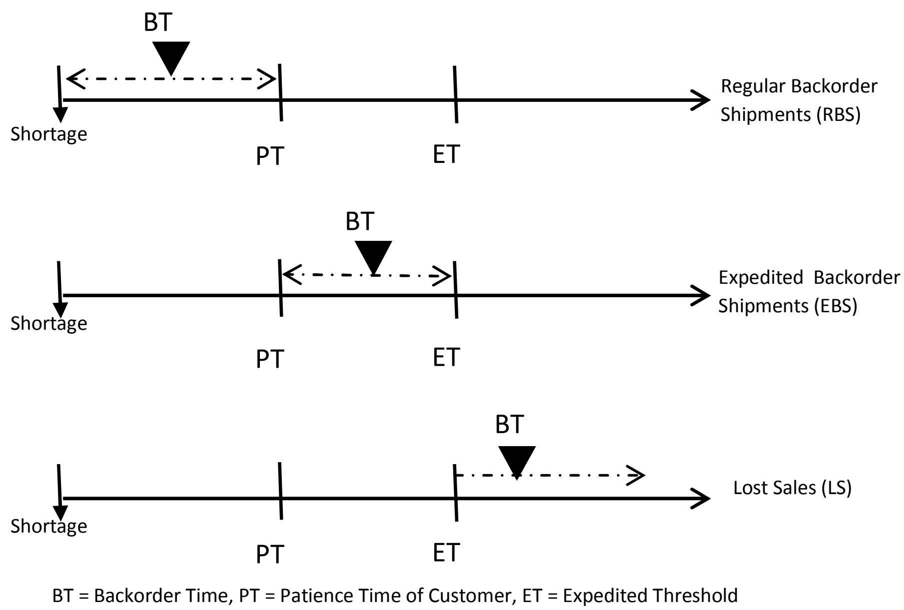


Figure 3.7: Expedited Shipments and Lost Sales Schematic

Example 3.3:

In this section we develop an empirical analysis to calculate Lost Sales and Expedited Shipments. For illustration, let us consider a network with Manufacturing Plant (P_1), Mixing Center (M_1), and Ramp (R_1). Let's assume daily constant outflow from R_1 and no off-setting of inflows and outflows. Let's assume the following parameters:

$X_{M1,R1}$=8, $r_{M1,R1}$=5, $X_{M1,R1}$=8, $r_{M1,R1}$=5, $X_{M1,R1}$=8, $r_{M1,R1=5}$, I_{i0} = 0, Patience (PT) = 1 time unit, and Expedited Threshold (ET) = 4 time units.

The net flow column in Table 3.4a shows the results of the unsold units plus the inflow units minus the outflow units in each time units. As we can see the total inflow is 18 units, the unsold unit is zero and the total outflow is 5 units resulting in a net flow of 13 units in time period 1. The cumulative inventory column adds up the inventory in the previous time unit to the net flow of the current time unit. The Backorder Time (BT) column identifies the number of time units (in days) a shortage will be met and positive inventory will be observed.

For example, the cumulative inventory is a shortage of 4 units in time period 8 and it will take at least 13 days to be positive. The column called Unit shortage per time unit is calculated to determine which units are candidate for Backorder Regular Shipments, which are for Backorder Expedited, and which are at risk for Lost Sales in the respective columns in Table 3.3a.

Time units	$x_{P1, R1}$	$x_{M1, R1}$	$x_{R1, DL1}$	Inflow to R_1	Outflow from R_1 (demand)	Netflow	Inventory (Cum)	BT (Back order Time)	Unit Shortage/ unit time	Backorder (Regular) BT <= PT	Backorder (Expedite) BT>PT and ET<=BT	Risk for Lost Sales BT>ET	Lost Sales units
1	10	8	5	13	5	13	13						
2	0	0	5	0	5	-5	8						
3	0	0	5	0	5	-5	3						
4	0	0	5	0	5	-5	-2	1	(2)	2			
5	0	8	5	8	5	3	1						
6	10	0	5	10	5	5	6						
7	0	0	5	0	5	-5	1						
8	0	0	5	0	5	-1	0						4
9	0	8	5	8	5	3	3						
10	0	0	5	0	5	-5	-2	1	(2)	2			
11	10	0	5	10	5	5	3						
12	0	0	5	0	5	0	3						5
13	0	8	5	8	5	3	6						
14	0	0	5	0	5	-5	1						
15	0	0	5	0	5	0	1						5
16	10	0	5	10	5	5	6						
17	0	8	5	8	5	3	9						
18	0	0	5	0	5	-5	4						
19	0	0	5	0	5	-5	-1	2	(1)		1		
20	0	0	5	0	5	-5	-6	1	(5)	5			

Table 3.3a: Lost Sales and expedited shipments

Time units	$X_{P1, R1}$	$X_{M1, R1}$	$X_{R1, DL1}$	Inflow to R_1	Outflow from R_1 (demand)	Netflow	Inventory (Cum)	BT (Back order Time)	Unit Shortage/ unit time	Backorder (Regular) BT <= PT	Backorder (Expedite) BT>PT and ET<=BT	Risk for Lost Sales BT>ET	Lost Sales units
1	10	8	5	18	5	13	13						
2	0	0	5	0	5	-5	8						
3	0	0	5	0	5	-5	3						
4	0	0	5	0	5	-5	-2	1	(2)	2			
5	0	8	5	8	5	3	1						
6	10	0	5	10	5	5	6						
7	0	0	5	0	5	-5	1						
8	0	0	5	0	5	-5	-4	13	(4)			4	
9	0	8	5	8	5	3	-1	12					
10	0	0	5	0	5	-5	-6	11	(5)			5	
11	10	0	5	10	5	5	-1	10					
12	0	0	5	0	5	-5	-6	9	(5)			5	
13	0	8	5	8	5	3	-3	8					
14	0	0	5	0	5	-5	-8	7	(5)			5	
15	0	0	5	0	5	-5	-13	6	(5)			5	
16	10	0	5	10	5	5	-8	5					
17	0	8	5	8	5	3	-5	4					
18	0	0	5	0	5	-5	-10	3	(5)		5		
19	0	0	5	0	5	-5	-15	2	(5)		5		
20	0	0	5	0	5	-5	-20	1	(5)	5			

Table 3.3b: Lost Sales and expedited shipments

In Table 3.3b, the Lost Sales and Expedited Shipment policies are applied: backorders are placed on regular shipments for instance when BT is less than or equal to the customer patience time (PT); backorders for expedited shipments are placed when BT is greater than the customer patience but less than or equal to the Expedited Threshold Time (ET) to have the order within the customer patience time. The Expedited Threshold is a managerial decision based on the cost of lost sales versus the cost of expedited shipments and customer patience time i.e. how long the customer is willing to wait to get the vehicle of choice.

In the above example, a total of 80 units were met within the time period that includes 4 units of backorder regular shipments against a demand of 100 units. There are 5 units of back order regular shipments and 1 unit of expedited shipments that are due in the next period. The estimated lost in this period is 14 units.

3.5.3 Regression Model

In this section, we develop regression models to estimate Lost Sales and Expedited Shipments. Our analysis is based on the service rate (fill rate) of the ramps to the demand by the dealers. We used 95%, 90%, 85%, 80%, and 75% service (fill) rate in our analysis. We assumed total demand is 100 units per time period. The demand is distributed with a mean of 5 units and a variance of 0 units per time unit. There are twenty time units in each time period. We modeled the random demand with stochastic stationary assumptions. We used a MatLab simulation platform to test our model. We used different combinations of Patience and Expedited Threshold Time (PT, ET) for a given service rate respectively. The (PT, ET) combinations we used are: (1,1), (1,2) (1,3), (1,4), (1,5), (2,2), (2,3), (2,4), (2,5), (3,3), (3,4), (3,5), (4,4), (4,5), and (5,5). The outputs of the simulation are the Regular Backorder Time (BT), Expedited Backorder Time (ET) and the Lost Sales for each combination.

In Table 3.4, we performed regression analysis on Expedited Shipments as a function of input parameters shipment size and ship frequency for two inflows to a ramp. One interesting observation is that the intercept and the co-efficient of the regression line are zero making Expected Shipment to be zero for

PT equal to ET. Another interesting observation is that the co-efficient of the two inflows are very close to each other. The lowest mean squared error .39402 was attained at PT = 4 and ET = 5.

In Table 3.5, we performed regression analysis on Expedited Shipments as a function of input parameters shipment size and ship frequency and regular shipments (R) for two inflows to a ramp. Again for asymmetric inflow data, the co-efficient (b_1, and b_2) are very close to each other. The lowest mean squared error .35572 was attained at PT = 4 and ET = 5.

In Table 3.6, we performed regression analysis on Expedited Shipments as a function of input parameters shipment size, ship frequency, regular shipments (R), and Lost Sales for two inflows to a ramp. For asymmetric inflow data, the co-efficient (b_1 and b_2) are very close to each other. The lowest mean squared error .33365 was attained at PT = 3 and ET = 4.

Function	PT	ET	mse	b_o	b_1	b_2
E = f(Inflows)	1	2	2.29407	24.59449	-0.24593	-0.25800
E = f(Inflows)	1	3	3.21359	45.63561	-0.46829	-0.47118
E = f(Inflows)	1	4	3.50377	54.17793	-0.56011	-0.56517
E = f(Inflows)	1	5	2.85760	64.54038	-0.67385	-0.66926
E = f(Inflows)	2	3	0.45795	20.56443	-0.21746	-0.21004
E = f(Inflows)	2	4	1.35420	29.15799	-0.30874	-0.30523
E = f(Inflows)	2	5	2.25986	38.81241	-0.41534	-0.40126
E = f(Inflows)	3	4	0.53074	8.45914	-0.09006	-0.09380
E = f(Inflows)	3	5	1.06313	16.88911	-0.18273	-0.18010
E = f(Inflows)	4	5	0.39402	8.33783	-0.09163	-0.08549

Table 3.4: Backorder Expedited Shipments as a function of Inflows for different combination of PT andET

Function	PT	ET	mse	b_o	b_1	b_2	b_3
E = f(Inflows, R)	1	2	1.53804	13.63998	-0.14858	-0.16077	0.25074
E = f(Inflows, R)	1	3	2.11892	33.16482	-0.35765	-0.36162	0.28361
E = f(Inflows, R)	1	4	3.10898	46.44681	-0.49139	-0.49751	0.17554
E = f(Inflows, R)	1	5	2.52796	57.62962	-0.61247	-0.60864	0.15689
E = f(Inflows, R)	2	3	0.45062	19.24972	-0.20525	-0.19769	0.01899
E = f(Inflows, R)	2	4	1.27107	33.35541	-0.34771	-0.34468	-0.06071
E = f(Inflows, R)	2	5	2.05655	45.40099	-0.47663	-0.46295	-0.09489
E = f(Inflows, R)	3	4	0.43454	14.22475	-0.14537	-0.14899	-0.06415
E = f(Inflows, R)	3	5	0.77604	26.74218	-0.27747	-0.27427	-0.10753
E = f(Inflows, R)	4	5	0.35572	12.51797	-0.13223	-0.12589	-0.04169
Note: R = Back order Regular Shipments							

Table 3.5: Backorder Expedited Shipments as a function of Inflows and Regular Shipments for different combination of PT and ET

In Table 3.7, we performed regression analysis on Lost Sales as a function of input parameters shipment size and ship frequency for two inflows to a ramp. One interesting observation is that the co-efficient of the two inflows are very close to each other. The lowest mean squared error 1.29682 was attained at PT = 1 and ET = 1.

In Table 3.8, we performed regression analysis on Lost Sales as a function of input parameters shipment size, ship frequency and regular shipments (R) for two inflows to a ramp. For asymmetric inflow data, the co-efficient (b_1, and b_2) are very close to each other. The lowest mean squared error 1.29868 was attained at PT = 1 and ET = 1.

Function	PT	ET	mse	b_o	b_1	b_2	b_3	b_4
E = *f*(Inflows,, R, L)	1	2	1.19511	31.50019	-0.34197	-0.34697	0.25689	-0.35638
E = *f*(Inflows,, R, L)	1	3	1.80799	44.23809	-0.48160	-0.47951	0.31385	-0.37366
E = *f*(Inflows,, R, L)	1	4	2.28053	55.30798	-0.59983	-0.59512	0.28575	-0.54768
E = *f*(Inflows,, R, L)	1	5	2.27635	59.96303	-0.64630	-0.63770	0.23937	-0.34971
E = *f*(Inflows,, R, L)	2	3	0.43666	16.79012	-0.17818	-0.17186	0.01758	0.07825
E = *f*(Inflows,, R, L)	2	4	1.21300	36.02270	-0.37870	-0.37279	-0.04782	-0.14246
E = *f*(Inflows,, R, L)	2	5	2.05085	45.81872	-0.48236	-0.46772	-0.08604	-0.06040
E = *f*(Inflows,, R, L)	3	4	0.33365	17.23522	-0.18081	-0.18086	-0.04711	-0.18186
E = *f*(Inflows,, R, L)	3	5	0.74125	27.13946	-0.28430	-0.27949	-0.08908	-0.12310
E = *f*(Inflows,, R, L)	4	5	0.34297	12.26400	-0.12813	-0.12265	-0.05153	0.07314
Note: R = Back order Regular Shipments, L = Lost sales								

Table 3.6: Backorder Expedited Shipments as a function of Inflows, Regular Shipments, and Lost Sales for different combination of PT and ET

In Table 3.9, we performed regression analysis on Lost Sales as a function of input parameters shipment size, ship frequency, regular shipments (R), and Expedited Shipments for two inflows to a ramp. For asymmetric inflow data, the co-efficient (b_1 and b_2) are very close to each other. The lowest mean squared error 1.30016 was attained at PT = 1 and ET = 1.

Function	PT	ET	mse	b_o	b_1	b_2
L = f(Inflows)	1	1	1.29682	69.77382	-0.73786	-0.72549
L = f(Inflows)	1	2	2.71355	50.86911	-0.54936	-0.52918
L = f(Inflows)	1	3	2.33229	33.19354	-0.36328	-0.34677
L = f(Inflows)	1	4	3.29399	25.04271	-0.27679	-0.25579
L = f(Inflows)	1	5	2.83523	17.06081	-0.18898	-0.17422
L = f(Inflows)	2	2	2.57898	51.06985	-0.55156	-0.53142
L = f(Inflows)	2	3	2.38919	32.67058	-0.35743	-0.34166
L = f(Inflows)	2	4	3.13359	24.97499	-0.27559	-0.25606
L = f(Inflows)	2	5	2.88407	17.08499	-0.18935	-0.17420
L = f(Inflows)	3	3	2.33614	33.06121	-0.36215	-0.34472
L = f(Inflows)	3	4	3.26759	24.97642	-0.27567	-0.25589
L = f(Inflows)	3	5	2.92433	16.95926	-0.18750	-0.17364
L = f(Inflows)	4	4	3.30769	25.26084	-0.27888	-0.25844
L = f(Inflows)	4	5	2.88032	16.96557	-0.18722	-0.17464
L = f(Inflows)	5	5	2.76325	16.77453	-0.18582	-0.17104

Table 3.7: Lost Sales as a function of Inflows for different combination of PT and ET

Function	PT	ET	mse	b_o	b_1	b_2	b_3
L = f(Inflows, R)	1	1	1.29868	69.87588	-0.73877	-0.72641	-0.00232
L = f(Inflows, R)	1	2	2.71398	50.11558	-0.54266	-0.52249	0.01725
L = f(Inflows, R)	1	3	2.24621	29.63474	-0.33170	-0.31550	0.08093
L = f(Inflows, R)	1	4	2.77315	16.17936	-0.19800	-0.17822	0.20124
L = f(Inflows, R)	1	5	2.08498	6.67240	-0.09672	-0.08310	0.23585
L = f(Inflows, R)	2	2	2.56396	53.10609	-0.57044	-0.55077	-0.02973
L = f(Inflows, R)	2	3	2.38561	31.43076	-0.34591	-0.33000	0.01790
L = f(Inflows, R)	2	4	2.94933	18.72265	-0.21754	-0.19731	0.09043
L = f(Inflows, R)	2	5	2.39602	6.91557	-0.09475	-0.07898	0.14646
L = f(Inflows, R)	3	3	2.32041	30.55223	-0.33812	-0.32069	0.02795
L = f(Inflows, R)	3	4	3.06546	16.55359	-0.19487	-0.17527	0.09372
L = f(Inflows, R)	3	5	2.36796	3.22727	-0.05545	-0.04241	0.14986
L = f(Inflows, R)	4	4	3.19759	18.17952	-0.21037	-0.18976	0.07216
L = f(Inflows, R)	4	5	2.47949	3.47252	-0.05615	-0.04424	0.13456
L = f(Inflows, R)	5	5	2.31897	0.75892	-0.02865	-0.01556	0.14728

Note: R = Back order Regular Shipments

Table 3.8: Lost Sales as a function of Inflows and Regular Shipments for different combination of PT andET

Function	PT	ET	mse	b_o	b_1	b_2	b_3	b_4
L = ƒ(Inflows, R, E)	1	1	1.30061	69.87588	-0.73877	-0.72641	-0.00232	0.00000
L = ƒ(Inflows, R, E)	1	2	2.10886	58.69322	-0.63610	-0.62359	0.17493	-0.62886
L = ƒ(Inflows, R, E)	1	3	1.91660	42.77149	-0.47337	-0.45874	0.19327	-0.39610
L = ƒ(Inflows, R, E)	1	4	2.03419	38.86972	-0.43806	-0.42127	0.28700	-0.48852
L = ƒ(Inflows, R, E)	1	5	1.87745	23.29444	-0.27337	-0.25865	0.28110	-0.28843
L = ƒ(Inflows, R, E)	2	2	2.56776	53.10609	-0.57044	-0.55077	-0.02973	0.00000
L = ƒ(Inflows, R, E)	2	3	2.31169	23.45594	-0.26088	-0.24811	0.01004	0.41428
L = ƒ(Inflows, R, E)	2	4	2.81460	29.74880	-0.33248	-0.31124	0.07036	-0.33057
L = ƒ(Inflows, R, E)	2	5	2.38937	10.11068	-0.12829	-0.11156	0.13978	-0.07038
L = ƒ(Inflows, R, E)	3	3	2.32385	30.55223	-0.33812	-0.32069	0.02795	0.00000
L = ƒ(Inflows, R, E)	3	4	2.35372	34.80313	-0.38138	-0.36641	0.01141	-1.28294
L = ƒ(Inflows, R, E)	3	5	2.26182	13.27226	-0.15968	-0.14543	0.10947	-0.37562
L = ƒ(Inflows, R, E)	4	4	3.20234	18.17952	-0.21037	-0.18976	0.07216	0.00000
L = ƒ(Inflows, R, E)	4	5	2.39059	-2.90891	0.01126	0.01994	0.15581	0.50978
L = ƒ(Inflows, R, E)	5	5	2.32241	0.75892	-0.02865	-0.01556	0.14728	0.00000
Note: R = Back order Regular Shipments, L = Lost sales								

Table 3.9: Lost Sales as a function of Inflows, Regular Shipments, and Expedited Shipments for different combination of PT andET

Function	PT	ET	mse	b_o	b_1
E = ƒ(Inflows)	1	2	2.30796	24.66494	-0.25057
E = ƒ(Inflows)	1	3	3.20983	45.65250	-0.46940
E = ƒ(Inflows)	1	4	3.50163	54.20745	-0.56206
E = ƒ(Inflows)	1	5	2.85588	64.51360	-0.67208
E = ƒ(Inflows)	2	3	0.46381	20.52109	-0.21461
E = ƒ(Inflows)	2	4	1.35366	29.13752	-0.30739
E = ƒ(Inflows)	2	5	2.28004	38.73019	-0.40992
E = ƒ(Inflows)	3	4	0.53161	8.48096	-0.09150
E = ƒ(Inflows)	3	5	1.06238	16.87380	-0.18172
E = ƒ(Inflows)	4	5	0.39790	8.30199	-0.08927

Table 3.10: Expedited Shipments as a function of Inflows for different combination of PT and ET

Function	PT	ET	mse	b_o	b_1
L = *f*(Inflows)	1	1	1.313028	69.70165	-0.7331
L = *f*(Inflows)	1	2	2.757828	50.75131	-0.54159
L = *f*(Inflows)	1	3	2.361177	33.09715	-0.35692
L = *f*(Inflows)	1	4	3.341425	24.92011	-0.26871
L = *f*(Inflows)	1	5	2.856871	16.97465	-0.1833
L = *f*(Inflows)	2	2	2.623281	50.95227	-0.54381
L = *f*(Inflows)	2	3	2.415167	32.57849	-0.35136
L = *f*(Inflows)	2	4	3.174221	24.86095	-0.26807
L = *f*(Inflows)	2	5	2.907048	16.99651	-0.18352
L = *f*(Inflows)	3	3	2.368726	32.95943	-0.35545
L = *f*(Inflows)	3	4	3.309168	24.86094	-0.26806
L = *f*(Inflows)	3	5	2.942782	16.87835	-0.18217
L = *f*(Inflows)	4	4	3.352379	25.14148	-0.27101
L = *f*(Inflows)	4	5	2.894849	16.89209	-0.18238
L = *f*(Inflows)	5	5	2.785076	16.68824	-0.18013

Table 3.11: Lost Sales as a function of Inflows for different combination of PT and ET

We had asymmetric input data in our previous test data. We re-ran our analysis with symmetric input data for both Expedited Shipments and Lost Sales. In Table 3.10, the lowest mean squared error is .39790 for the Expedited Shipment was attained at PT=4 and ET=5. In Table 3.12, the lowest mean squared error is 1.313028 for the Lost Sales was attained at PT = 1 and ET = 1.

3.6 Multi-period, Multi-product MCNF Base Model with Lost Sales and Expedited Shipping

3.6.1 Assumptions

1. *Time:* The planning horizon consists of a finite number of time periods. Each time period has equal number of time units. For example, each time period is a month with 20 working days.
2. *Supply:* The aggregate production level in each period is determined according to the total demand, which is estimated by confirmed orders and forecasted demand. The production rate within each time period is constant.
3. *Demand:* The daily shipment volume of a ramp is the daily customer demand (monthly demand/number of working days) and the ship frequency of the ramp to the customer is daily. Shipments are made forward in the network. Backward shipments (Mixing Centers to Plant, Ramps to MixingCenter, and Ramps to the Plant are not allowed. When shipments are made directly from the plant to the ramp, there are no congestions and no inventory delays in the network.
4. *Mixing Center (MC):* The Mixing Centers are the transshipment point of the outbound logistics network. Vehicles are transported from the manufacturing plants to the Consolidation centers where vehicles get

unloaded, staged in the yard and reloaded onto the destination rail cars for next scheduled shipments.

This unloading, staging, and reloadingprocess contributes to the in-house inventory at the respective Mixing Centers.

3.6.2 Sets and Indices

P: Vehicle Assembly plants

M: Mixing (Consolidation) Centers

R: Ramps

A:Set of all nodes

T:Planning Horizon

i, j:Indices for nodes P, M, R

t:Indices for time period,$t \in T$

v: Indices for vehicle make and model type, $v \in V$

k:Indices for K

l:Indices for time units $l \in L$

3.6.3 Parameters and Notations

c_{ij}: Per unit transportation cost from node i to j

u_{ij}: Shipment capacity on arc (i, j)

τ_{ij}: Transportation time of each shipment going from node $i$to j

h_{ij}: Fixed cost charged by Carrier on each shipment on arc (i, j)

f_{ij} : Fixed cost for choosing arc (i, j) in planning horizon T

p_v : Holding cost per day per make and model type v

S_{ivt}: Supply/demand requirement at node i of make and model type$v$in time period t, $S_{ivt} > 0$for supply nodes, $S_{ivt} < 0$ for demand nodes, and $S_{ivt} = 0$for transshipment nodes

T: Number of time periods in the planning horizon

L:Total number of time units in time period t

I_{ivt}: Ending inventories at node i of make and model type v and time period t

3.6.4 Decision Variables

We define two types of decision variables in our model. The primary decisions variables are the exogenous variables and the variables dependent on the primary decision variables are the endogenous variables.

3.6.4.1 Exogenous Decision Variables

x_{ijvt}: Average number of vehicles transported from node i to j of make and model type v in time period t in each shipment

r_{ijt}: Ship frequency (# of shipments/ time period) from node i to j in time period t

y_{ijt}: Binary variable indicating whether there is flow on arc (i,j)in time period t

o_{ijt}: Shipment off-setting from node$i$ to $j$in time units from beginning of time period t

3.6.4.2 Endogenous Decision Variables

$\hat{r}_{ijt}$: Actualized ship frequency from node i to j arriving in time period$t$

$\hat{o}_{ijt}$: Actualized shipment off-setting from node$i$ to $j$in time units from beginning of time period t

q_{ivt}: Inventory accumulation rate (units/time period) at node $i$for vehicle make and model type v in time period t,$q_{ivt} > 0$,inventory build-up, and $q_{ivt} < 0$, inventory depletion

3.6.5 The MCNF Base Model

The multi-period multi-commodity MCNF optimization problem can now be formulated as follows:

$$
\begin{aligned}
Min \sum_{\substack{i,j,v,t \\ i\in P\cup M \\ j\in M\cup R \\ v\in V \\ t\in T}} c_{ij} x_{ijvt}\, r_{ijt} + \sum_{\substack{i,j,v,t \\ i\in P\cup M \\ j\in M\cup R \\ t\in T}} f_{ij}\, y_{ijt} + \sum_{\substack{i,j,v,t \\ i\in P\cup M \\ j\in M\cup R \\ t\in T}} h_{ij}\, r_{ijt} \\
+ \left[\sum_{\substack{i,v,t \\ i\in P \\ v\in V \\ t\in T}} \left(I_{ivt} + \left(\frac{r_{0it}+1}{2}\right) x_{0ivt} - \sum_{j\in M\cup R} \left(\frac{r_{ijt}+1}{2}\right) x_{ijvt} \right)\right] p_v\, L \\
+ \left[\sum_{\substack{i,v,t \\ i\in M \\ v\in V \\ t\in T}} \left(I_{ivt} + \sum_{\substack{j,(j\neq i) \\ j\in P\cup M}} \left(\frac{r_{jit}+1}{2}\right) x_{jivt} - \sum_{\substack{j,(j\neq i) \\ j\in M\cup R}} \left(\frac{r_{ijt}+1}{2}\right) x_{ijvt} \right)\right] p_v\, L \\
+ \left[\sum_{\substack{i,v,t \\ i\in R \\ v\in V \\ t\in T}} \left(I_{ivt} + \sum_{\substack{j,(j\neq i) \\ j\in P\cup M}} \left(\frac{r_{jit}+1}{2}\right) x_{jivt} - \left(\frac{r_{iDt}+1}{2}\right) x_{iDvt} \right)\right] p_v\, L \\
+ \left(\sum_{\substack{i,j,v,t \\ i\in P\cup M \\ j\in M\cup R \\ v\in V \\ t\in T}} (x_{ijvt}\, r_{ijt}) \tau_{ij} \right) p_v + \sum_{\substack{j \\ t\in T \\ j\in M\cup R}} (Lost\ Sales_{jt} + Expediting_{jt})
\end{aligned}
$$

s.t.

$$q_{ivt} + \sum_{\substack{j \in M \cup R \\ j \neq i}} r_{ijt} x_{ijvt} - \sum_{\substack{j \in P \cup M \\ j \neq i}} r_{jit} x_{jivt} = 0 \quad \forall i \in M, v \in V, t \in T$$ (MC flow conservation)

$$q_{ivt} + \sum_{j \in M \cup R} r_{ijt} x_{ijvt} = s_{ivt} \quad \forall i \in P, v \in V, t \in T$$ (Plant flow conservation)

$$q_{ivt} - \sum_{j \in P \cup M} r_{jit} x_{jivt} = s_{ivt} \quad \forall i \in R, v \in V, t \in T$$ (Ramp Flow conservation)

$$r_{0it} x_{0itv} = s_{ivt} \quad \forall i \in P, \forall v \in V, \forall t \in T$$ (Plants production)

$$r_{iDvt} x_{Divt} = s_{ivt} \quad \forall i \in R, \forall v \in V, \forall t \in T$$ (Ramps demand)

$$I_{it} + \sum_{\substack{j \in P \cup M \\ j \neq i}} r_{jit} x_{jit} \geq \sum_{\substack{j \in M \cup R \\ j \neq i}} r_{ijt} x_{ijt} \quad \forall i \in M, \forall v \in V, \forall t \in T$$ (Nonnegative MC Inventory in each period)

$$I_{ivt} + r_{0it} x_{0ivt} \geq \sum_{j \in M \cup R} r_{ijt} x_{ijvt} \quad \forall i \in P, \forall v \in V, \forall t \in T$$ (Nonnegative Plant Inventory in each period)

$$I_{ivt} + \sum_{j \in P \cup M} r_{jit} x_{jivt} \geq r_{iDt} x_{iDvt} \;\; \forall i \in R, \forall v \in V, \forall t \in T$$ (Nonnegative Ramp Inventory in each period)

Nonnegative Average Inventory Condition in each period

$$I_{ivt} + \sum_{\substack{j \in P \cup M \\ j \neq i}} x_{jivt} \geq \sum_{\substack{j \in M \cup R \\ j \neq i}} x_{ijvt} \;\; \forall i \in M, \forall v \in V, \forall t \in T$$

$$I_{ivt} + x_{0ivt} \geq \sum_{j \in M \cup R} x_{ijvt} \;\; \forall i \in P, \forall v \in V, \forall t \in T$$

$$I_{ivt} + \sum_{j \in P \cup M} x_{jivt} \geq x_{iDvt} \;\; \forall i \in R, \forall v \in V, \forall t \in T$$

$$x_{ijvt} \leq u_{ij} \;\; \forall i \in P \cup M, j \in M \cup R, j \neq i, \forall v \in V, \forall t \in T$$ (Arc flow capacity)

$$x_{ijvt} \leq M y_{ijt} \;\; \forall i \in P \cup M, j \in M \cup R, j \neq i, \forall v \in V, \forall t \in T$$ (No flow if arc not selected)

$$y_{ijt} \leq r_{ijt} \;\; \forall i \in P \cup M, j \in M \cup R, j \neq i, \forall t \in T$$ (no need to select arc if not shipping)

$$\sum_{t=1}^{T} q_{ivt} = 0 \quad \forall i \in P \cup M \cup R, \forall v \in V$$ (Inventory conservation)

$$I_{iv1} + \sum_{t'=1}^{t} q_{ivt'} \geq 0 \quad \forall i \in P \cup M \cup R \;\; where, t = 1,2,3 \ldots T-1, \qquad \forall v \in V \tag{7}$$

No need for $t = T$ since for the case, $t = T$ the left hand side summation of q_{it} is 0 as per the previous constraint.

$$x_{0ivt} \geq 0 \quad \forall i \in P, \forall v \in V \tag{8}$$

$$x_{iDt} \geq 0 \quad \forall i \in R, \;\; \forall v \in V \tag{9}$$

$$x_{ijvt} \geq 0 \quad \forall i \in P \cup M, j \in M \cup R, \quad \forall v \in V \tag{10}$$

$$y_{ijt} = \{0, 1\} \;\; \forall i \in P \cup M, j \in M \cup R \tag{11}$$

$$r_{0it} \geq 0 \quad \forall i \in P, \;\; r_{iDt} \geq 0 \quad \forall i \in R, \quad r_{ijt} \;\in Z_{+} \forall i \in P \cup M, j \in M \cup R \tag{12}$$

3.6.6 The MCNF Base Model Reformulation

In this section, we introduce an alternative reformulation strategy for the multi-period MCNF problem. The resulting model will no longer have non-linearity in the objective function and the constraint set thus making it an integer linear programming (ILP) model and can be solved via classical ILP solvers.

In our model the average number shipments per time period x_{ijt} is a continuous variable and the ship frequency r_{ijt} is an integer variable. Hence, the multiplication term $x_{ijvt}\, r_{ijt}$ is a non-linear term. In order to make the multiplication term linear, we will convert r_{ijt} into summation of series of binary variables such that the multiplication term becomes linear.

Continuous * integer $\longrightarrow$ Non-linear

Continuous*binary $\longrightarrow$ Linear

We present several new binary variables and constraints to convert the non-linear functions to linear functions of the initial MCNF problem. Before we introduce the binary variables and constraints, we define the ship frequency as,

$$r_{ijt} = \sum_{k=1}^{K} 2^{k-1} z_{kijt}$$

Multiplying both sides by x_{ijvt}, we get, $x_{ijvt} r_{ijt} = \sum_{k=1}^{K} 2^{k-1} x_{ijvt} z_{kijt}$

Substituting, the $w_{kijvt} = x_{ijvt} z_{kijt}$ term with$w_{kijvt},$

We get, $x_{ijvt} r_{ijt} = \sum_{k=1}^{K} 2^{k-1} w_{kijvt}$

Similarly, for the inflow to node i we have: $x_{jivt} r_{jit} = \sum_{k=1}^{K} 2^{k-1} w_{kjivt}$

We can now substitute the non-linear terms ($x_{ijvt} r_{ijt}$ and$x_{jivt} r_{jit}$) into the initial model and derive the revised model formulation as follows:

$$Min \sum_{\substack{i,j(j\neq i),t \\ i\in P\cup M \\ j\in M\cup R \\ v\in V \\ t\in T}} \sum_{k=1}^{K} 2^{k-1}\, c_{ij} w_{kijvt} + \sum_{\substack{i,j(j\neq i),t \\ i\in P\cup M \\ j\in M\cup R \\ t\in T}} f_{ij}\, y_{ijt} + \sum_{\substack{i,j,(j\neq i),t \\ i\in P\cup M \\ j\in M\cup R \\ t\in T}} h_{ij}\, r_{ijt}) +$$

s.t.

$$q_{ivt} + \sum_{\substack{j\in M\cup R \\ j\neq i}} \sum_{k=1}^{K} 2^{k-1} w_{kijvt} - \sum_{\substack{j\in P\cup M \\ j\neq i}} \sum_{k=1}^{K} 2^{k-1} w_{kjivt} = 0 \quad \forall i \in M, v \in V, t \in T$$

(MC flow conservation)

$$q_{ivt} + \sum_{j\in M\cup R} \sum_{k=1}^{K} 2^{k-1} w_{kijvt} = s_{ivt} \qquad \forall i \in P, v \in V, t \in T$$

(Plant flow conservation)

$$q_{ivt} - \sum_{j\in P\cup M} \sum_{k=1}^{K} 2^{k-1} w_{kjivt} = s_{ivt} \qquad \forall i \in R, v \in V, t \in T$$

(Ramp Flow conservation)

$$\sum_{k=1}^{K} 2^{k-1} w_{k0ivt} = s_{ivt} \quad \forall i \in P, v \in V, t \in T$$

(Plants production)

$$\sum_{k=1}^{K} 2^{k-1} w_{kiDvt} = -s_{ivt} \quad \forall i \in R, v \in V, t \in T$$

(Ramps demand)

$$I_{ivt} + \sum_{\substack{j\in P\cup M \\ j\neq i}} \sum_{k=1}^{K} 2^{k-1} w_{kjivt} \geq \sum_{\substack{j\in M\cup R \\ j\neq i}} \sum_{k=1}^{K} 2^{k-1} w_{kijvt}$$

$$\forall i \in M, v \in V, t \in T$$

(Nonnegative MC Inventory in each period)

$$I_{ivt} + \sum_{k=1}^{K} 2^{k-1} w_{k0ivt} \geq \sum_{j\in M\cup R} \sum_{k=1}^{K} 2^{k-1} w_{kijvt} \quad \forall i \in P, v \in V, t \in T$$

(Nonnegative Plant Inventory in each period)

$$I_{ivt} + \sum_{j\in P\cup M} \sum_{k=1}^{K} 2^{k-1} w_{kjivt} \geq \sum_{k=1}^{K} 2^{k-1} w_{kiDvt} \quad \forall i \in R, v \in V, t \in T$$

(Nonnegative Ramp Inventory in each period)

Nonnegative Average Inventory Condition in each period

$$I_{ivt} + \sum_{\substack{j\in P\cup M \\ j\neq i}} x_{jivt} \geq \sum_{\substack{j\in M\cup R \\ j\neq i}} x_{ijvt} \quad \forall i \in M, v \in V, t \in T$$

$$I_{ivt} + x_{0ivt} \geq \sum_{j\in M\cup R} x_{ijvt} \quad \forall i \in P, v \in V, t \in T$$

$$I_{ivt} + \sum_{j\in P\cup M} x_{jivt} \geq x_{iDvt} \quad \forall i \in R, v \in V, t \in T$$

$$x_{ijvt} \leq u_{ij} \quad \forall i \in P \cup M, j \in M \cup R, j \neq i, \forall v \in V, \forall t \in T$$ (Arc flow capacity)

$$x_{ijvt} \leq M y_{ijt} \quad \forall i \in P \cup M, j \in M \cup R, j \neq i, \forall v \in V, \forall t \in T$$ (No flow if arc not selected)

$$y_{ijt} \leq r_{ijt} \quad \forall i \in P \cup M, j \in M \cup R, j \neq i, \forall t \in T$$ (no need to select arc if not shipping)

$$\sum_{t=1}^{T} q_{ivt} = 0 \quad \forall i \in P \cup M \cup R, \forall v \in V$$ (Inventory conservation)

$$I_{iv1} + \sum_{t'=1}^{t} q_{ivt'} \geq 0 \quad \forall i \in P \cup M \cup R \ \ where, t = 1,2,3 \ldots T-1, \qquad \forall v \in V \tag{7}$$

No need for $t = T$ since for the case $t = T$, the left hand side summation of q_{it} is 0 as per the previous constraint.

$$r_{0it} = \sum_{k=1}^{K} 2^{k-1} z_{k0it} \qquad \forall i \in P, t \in T \tag{8}$$

$$r_{iDt} = \sum_{k=1}^{K} 2^{k-1} z_{kiDt} \qquad \forall i \in R, t \in T \tag{9}$$

$$r_{ijt} = \sum_{k=1}^{K} 2^{k-1} z_{kijt} \qquad \forall i \in P \cup M, \forall j \in M \cup R, j \neq i, t \in T \quad (10)$$

$$w_{kijvt} \geq x_{ijvt} - \Upsilon\left(1 - z_{kijt}\right)$$

$$\forall i \in P \cup M, \forall j \in M \cup R, j \neq i, \forall v \in V, \forall t \in T, k \in K$$

$$w_{kijvt} \leq x_{ijvt} + \Upsilon\left(1 - z_{kijt}\right)$$

$$\forall i \in P \cup M, \forall j \in M \cup R, j \neq i, \forall v \in V, \forall t \in T, k \in K$$

$$w_{kijvt} \leq \Upsilon z_{kijt} \qquad \forall i \in P \cup M, \forall j \in M \cup R, j \neq i, \forall v \in V, \forall t \in T, k \in K$$

$$w_{k0ivt} \geq x_{0ivt} - \Upsilon(1 - z_{k0it}) \qquad \forall i \in P, \forall v \in V, \forall t \in T, k \in K$$

$$w_{k0ivt} \leq x_{0ivt} + \Upsilon(1 - z_{k0it}) \qquad \forall i \in P, \forall v \in V, \forall t \in T, k \in K$$

$$w_{k0ivt} \leq \Upsilon z_{k0it} \qquad \forall i \in P, \forall v \in V, \forall t \in T, k \in K$$

$$w_{kiDvt} \geq x_{iDvt} - \Upsilon(1 - z_{kiDt}) \qquad \forall i \in R, \forall v \in V, \forall t \in T, k \in K$$

$$w_{kiDvt} \leq x_{iDvt} + \Upsilon(1 - z_{kiDt}) \qquad \forall i \in R, \forall v \in V, \forall t \in T, k \in K$$

$$w_{kiDvt} \leq \Upsilon z_{kiDt} \qquad \forall i \in R, \forall v \in V, \forall t \in T, k \in K$$

$$x_{0ivt} \geq 0 \quad \forall i \in P, \forall v \in V \qquad (11)$$

$$x_{iDvt} \geq 0 \quad \forall i \in R,\ \forall v \in V\ \ x_{ijvt} \geq 0$$
$$\forall i \in P \cup M, j \in M \cup R, j \neq i,\ \ \forall v \in V \tag{12}$$

$$w_{k0it} \geq 0 \quad \forall i \in P,\ \ w_{kiDt} \geq 0$$
$$\forall i \in R,\ \ \ w_{kijt} \geq 0 \quad \forall i \in P \cup M, j \in M \cup R, j \neq i \tag{13}$$

$$y_{ijt} = \{0, 1\} \ \ \forall i \in P \cup M, j \in M \cup R, j \neq i \tag{14}$$

$$z_{kijt} = \{0, 1\} \ \ \forall i \in P \cup M, j \in M \cup R, j \neq i, \forall t \in T, k \in K$$
$$z_{k0it} = \{0, 1\} \ \ \forall i \in P, \forall t \in T, k \in K \tag{15}$$
$$z_{kiDt} = \{0, 1\} \ \ \forall i \in R, \forall t \in T, k \in K$$

$$r_{0it} \geq 0 \quad \forall i \in P,\ \ r_{iDt} \geq 0 \quad \forall i \in R,\ \ \ r_{ijt}\ \in Z_+\ \forall i \in P \cup M, j \in M \cup R, j \neq i \tag{16}$$

3.7 Experimental Study

In this section, we discuss the results of an experimental study conducted for understanding the effect of logistics system parameters on such performance measures as total system cost, various logistics costs by type, echelon and facility type. We consider a single OEM and with and without intra-company collaboration. In the case of collaboration, the OEM's plants and mixing centers can transship vehicles so as to realize economies of scale in fixed costs, e.g., fixed arc selection and fixed transshipment costs. Further, collaboration allows reducing the inventory costs through more frequent shipments which are cost effective due to the consolidation effect. The base models used in these experiments are the formulations presented in Table 3.12 and 3.13. Note that both of these models are multi-product and account for the lost sales and expediting. In all experiments, we have used the same data set except the logistics system parameters related to the collaboration, e.g. fixed and variable transportation costs between the facilities in the same echelon and the corresponding arc capacities. The summary of the parameter settings used in the experimentation is as follows:

		Scenarios Used	
Paramateter List	**Baseline**	**Without Collaboration**	**With Collaboration**
Transportation Cost (c_{ijv})	c^0_{ijv}	Δc^0_{ijv}={**0%**, ±10%, ±20%}	Δc^0_{ijv}={**0%**, ±20%}
Ramp Service Level (SL)	SL^0	SL={1,0.9,0.8,**0.7**,0.6}	SL={1,**0.7**,0.6}
Arc Capacity (u_{ij})	u^0_{ij}	Δu^0_{ij}={**0%**, ±20%, ±40%}	Δu^0_{ij}={**0%**, ±40%}
Arc Fixed Cost (f_{ij})	f^0_{ij}	Δf^0_{ij}={**0%**, ±25%, ±50%}	Δf^0_{ij}={**0%**, ±50%}
Per Shipment Fixed Cost (h_{ij})	h^0_{ij}	Δh^0_{ij}={**0%**, ±25%, ±50%}	Δh^0_{ij}={**0%**, ±50%}
Facility Inventory Holding Cost (pf_{iv})	pf^0_{iv}	Δpf^0_{iv}={**0%**, ±15%, ±30%}	Δpf^0_{iv}={**0%**, ±30%}
In-transit Inventory Holding Cost (pt_v)	pt^0_v	Δpt^0_v={**0%**, ±15%, ±30%}	Δpt^0_v={**0%**, ±30%}

Table 3.12. Total variable cost transportation component by echelon, product andperiod.

Due to the length labels, we have used short forms for different logistics system performance parameters in the remainder of the section. These short forms are depicted in the following table.

Next, we first present and discuss the results of the experiments conducted without the collaboration.

Notation		Description
Total Cost	:	Total logistics system cost
TRPC	:	Total transportation variable cost
FCA	:	Total fixed cost of selecting arcs
FCPS	:	Total per shipment fixed cost
FIHC	:	Total cost of facility inventory holding
ITHC	:	Total cost of in-transit inventory holding
Expediting	:	Total cost of expediting
Lost Sales	:	Total cost of lost sales

Table 3.13. Total Variable Cost Transportation by echelon, product and period.

3.7.1Without Collaboration

In this section, we will compare the different performance parameters of the Outbound Logistics Network system where there are no collaboration.

3.7.1.1 Baseline Scenario

We first discuss the baseline scenario. The summary of variable transportation costs is summarized as below by echelon, by product and by period. While the demand for Product 1 is more than Product 2, the variable cost of transportation per unit Product 2 is higher than Product 1, thus their period costs are similar in both P-M and M-R echelons.

P-M	Product 1	Product 2	Total	M-R	Product 1	Product 2	Total
Period 1	1,090,567	1,085,300	**2,175,868**	**Period 1**	603,231	636,681	**1,239,912**
Period 2	1,099,947	1,163,919	**2,263,867**	**Period 2**	659,359	759,479	**1,418,837**
Period 3	1,160,513	1,184,027	**2,344,540**	**Period 3**	598,860	644,596	**1,243,456**
Total	**3,351,028**	**3,433,246**	**6,784,274**	**Total**	**1,861,449**	**2,040,756**	**3,902,206**

Table 3.14. Total Variable Cost Transportation by echelon, product and period.

Next table illustrates total fixed cost of selecting arcs within each echelon by period as well total fixed cost of shipments by period. Results show that the selection of arcs within the P-M echelon varies more by period than the M-R echelon. Also the total fixed cost of arc selection in the M-R echelon is higher than P-M since there are fewer arcs in the upstream than the downstream. Note that this difference in the number of arcs dominates the difference in the per arc fixed cost between echelons.

	P-M		M-R	
Fixed Cost Arc	**Period 1**	382,150	**Period 1**	536,595
	Period 2	261,100	**Period 2**	575,245
	Period 3	382,150	**Period 3**	523,495
	Total	**1,025,400**	**Total**	**1,635,335**
Fixed Cost Per Shipment	**Period 1**	375,600	**Period 1**	211,835
	Period 2	119,725	**Period 2**	286,045
	Period 3	426,125	**Period 3**	228,250
	Total	**921,450**	**Total**	**726,130**

Table 3.15. Fixed Cost Transportation by echelon and period.

The next table summarizes the inventory holding cost for the baseline scenario. Clearly, in all facilities, the holding cost is most initially due to the starting conditions and corresponding initial inventory levels. The next highest inventory level is in Period 3 which is due to the requirement that by the end of the planning horizon, the inventory levels should be identical to the starting levels. Note that period 3 inventory is still less than period 1 since the demand in first and second periods is met by the initial inventories. The minimum inventory levels are achieved in the Mixing Centers since they are transshipment points and have access to most inflow and outflow arcs. In contrast, the plants have only access to the mixing centers. The ramps on the other hand have some level of inventory due to the fact that shortages lead to expediting and lost sales. As a result the inventory levels are balanced between the expediting/lost sale cost and inventory holding cost.

	Plant			MC			Ramp		
	Product 1	**Product 2**	**Total**	**Product 1**	**Product 2**	**Total**	**Product 1**	**Product 2**	**Total**
Period 1	13,398	154,139	**167,537**	258,609	177,468	**436,077**	1,775,131	2,040,010	**3,815,141**
Period 2	3,937	0	**3,937**	0	0	**0**	21,941	11,266	**33,207**
Period 3	0	38,493	**38,493**	31,492	0	**31,492**	342,133	452,553	**794,686**
Total	**17,335**	**192,632**	**209,967**	**290,101**	**177,468**	**467,569**	**2,139,205**	**2,503,829**	**4,643,034**

Table 3.16. Fixed Cost Transportation by echelon and period.

3.7.1.2 Effect of Variable Transportation Cost

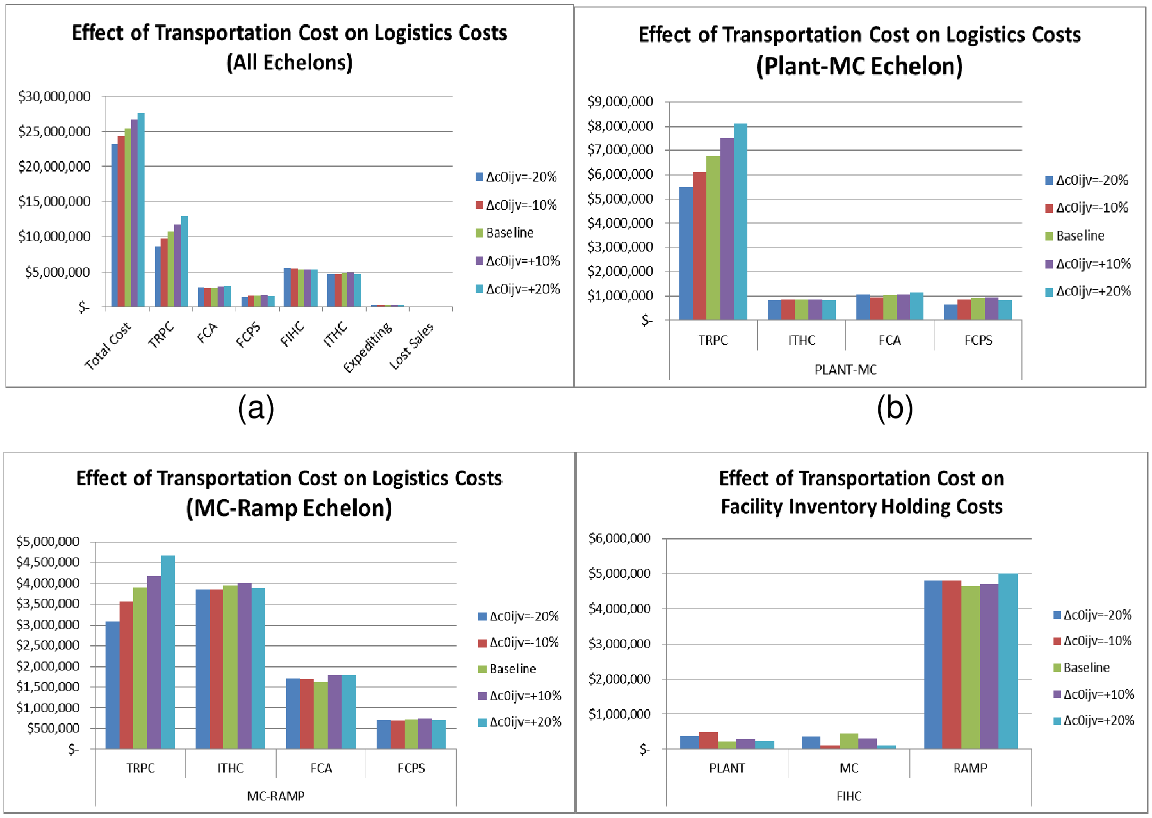
In what follows, we investigate the effect of changing cost parameters on the logistics system costs by type of cost, echelon, and facility. We first consider the effect of transportation cost parameter change on the logistics system performance. The results are displayed in Tables 3.17, 3.18 and Figure 3.8.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δc^0_{ijv}=-20%	23,245,693	8,577,368	2,789,885	1,389,665	5,546,445	4,689,321	253,009	-
Δc^0_{ijv}=-10%	24,326,101	9,672,731	2,653,935	1,566,275	5,425,340	4,719,004	288,815	-
Baseline	25,402,749	10,686,480	2,660,735	1,647,580	5,320,570	4,814,520	272,864	-
Δc^0_{ijv}=+10%	26,675,330	11,688,558	2,873,585	1,708,930	5,328,640	4,865,611	210,006	-
Δc^0_{ijv}=+20%	27,636,384	12,803,500	2,945,785	1,541,490	5,350,965	4,703,505	291,138	-

Table 3.17. Effect of changing Transportation Cost on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				FIHC		
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	PLANT	MC	RAMP
Δc^0_{ijv}=-20%	5,497,044	823,669	1,076,400	630,475	3,080,325	3,865,652	1,713,485	714,650	384,170	360,357	4,801,918
Δc^0_{ijv}=-10%	6,110,456	850,222	958,500	857,250	3,562,275	3,868,782	1,695,435	691,055	502,158	120,300	4,802,882
Baseline	6,784,274	855,565	1,025,400	921,450	3,902,206	3,958,955	1,635,335	726,130	209,967	467,569	4,643,034
Δc^0_{ijv}=+10%	7,504,410	852,389	1,076,400	959,000	4,184,148	4,013,222	1,797,185	749,930	300,118	323,511	4,705,011
Δc^0_{ijv}=+20%	8,118,172	815,014	1,146,450	831,025	4,685,328	3,888,491	1,799,335	710,465	236,254	109,669	5,005,042

Table 3.18. Effect of changing Transportation Cost on Logistics Costs by echelon and facility.



(a) (b)

(c) (d)

Figure 3.8. Effect of changing the transportation cost on Logistics Costs by type, echelon and facility type.

The results show that the increasing variable transportation cost parameter increases the total cost linearly. The changes on the other cost types are insignificant. Furthermore, the effect on different echelons and facilities are similar.

3.7.1.3 Effect of Service Level at Ramps

Service level corresponds to the extend we meet the demand at each ramp in eac period for each product. Hence greater service level requires that the inflow to each ramp in each period must increase. The results in Table XXX show the effect of service level on the cost elements of the entire logistics system (e.g. all echelons). There is no clear effect on the total cost components of all echelons except FIHC which increases with the service level. This is because the availability of supply at the ramp (either through inflow or through the inventory) should increase. Since there is such constraints as arc capacity and such cost factors as fixed shipment cost, the inventory is used as a means of icnreasing the availability required by increased service level. Therefore the FIHC is increased. We also see that this increased is nonlinear such that SL=0.6 to 08 have similar FIHC but SL=0.9 and 1.0 have significantly higher FHIC. Also we note that the expediting cost decreases with increased service level requirement which is expected.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
SL=1.0	32,857,673	10,817,712	2,284,145	1,593,975	13,058,128	5,103,712	-	-
SL=0.9	28,092,094	10,720,734	2,435,195	1,449,265	8,583,414	4,832,354	71,132	-
SL=0.8	25,566,969	10,826,891	2,771,840	1,320,135	5,889,891	4,576,950	181,262	-
Baseline (SL^0=0.7)	25,402,749	10,686,480	2,660,735	1,647,580	5,320,570	4,814,520	272,864	-
SL=0.6	25,616,487	10,758,529	2,811,240	1,666,475	5,357,548	4,744,681	278,014	-

Table 3.19. Effect of changing Ramp Service Level on Logistics Costs (All echelons).

When we analyze the effect of changing the service level in each echelon, we see differences between echelons. One observation is the the increase in the FCA with decreasing service level. This is counter intiutive since increasing service level induces the selection of more arcs. However, the decrease in FCA with increasing service level is to the contrary to this intuition. Further, while there is no particular pattern to the change in FCPS in the P-MC echelon, the MC-R echelon shows that the total fixed cost of per shipment tends to decrease with increasing service level. This can be explained by the fact that the larger the shipment size, the more the availaibility (we assume shipments occur from the beginning of each period) within each period. Hence, one way of attaining higher service level is to ship less frequently with larger shipment sizes. Last observation is for the inventory hodling cost at the facilities (FIHC). We observe that as we go upstream in the logistics network, the increasing service level increases the inventory levels more dramatically.

	PLANT-MC				MC-RAMP				FIHC		
Scenarios	**TRPC**	**ITHC**	**FCA**	**FCPS**	**TRPC**	**ITHC**	**FCA**	**FCPS**	**PLANT**	**MC**	**RAMP**
SL=1.0	6,980,556	907,360	833,950	909,275	3,837,157	4,196,352	1,450,195	684,700	3,250,830	2,131,877	7,675,421
SL=0.9	6,883,961	862,393	893,500	788,500	3,836,773	3,969,961	1,541,695	660,765	1,071,978	431,641	7,079,795
SL=0.8	6,930,469	799,791	1,025,400	558,400	3,896,422	3,777,159	1,746,440	761,735	221,105	381,627	5,287,159
Baseline (SL^0=0.7)	6,784,274	855,565	1,025,400	921,450	3,902,206	3,958,955	1,635,335	726,130	209,967	467,569	4,643,034
SL=0.6	6,805,516	843,711	1,076,400	905,625	3,953,013	3,900,970	1,734,840	760,850	275,773	382,188	4,699,587

Table 3.20. Effect of changing Transportation Cost on Logistics Costs by echelon and facility.

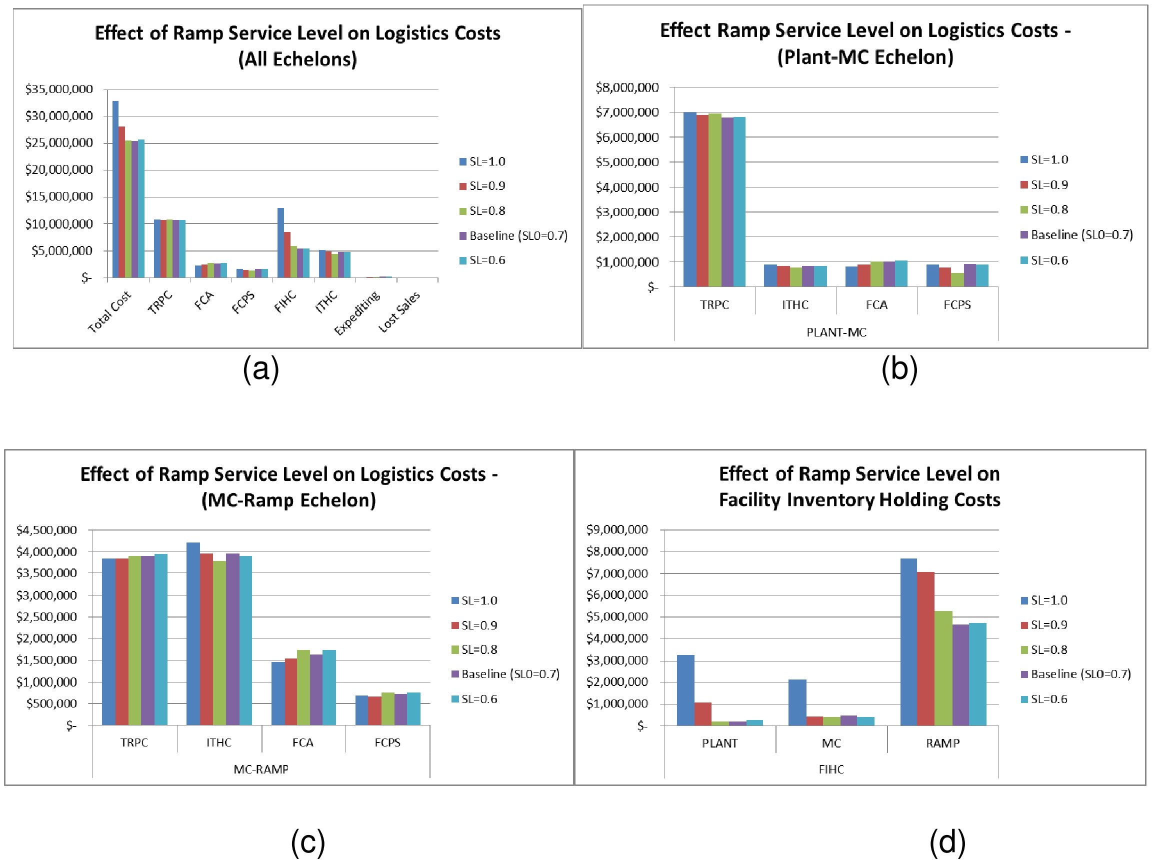


Figure 3.9. Effect of changing Ramp Service Level on Logistics Costs by type, echelon and facility type.

3.7.1.4 Effect of Per Shipment Fixed Cost

The effect of changing the per shipment fixed cost parameter is illustrated in Tables 3.21 and 3.22 as well as in Figure 3.10. Clearly the increasing per shipment fixed cost increases the total logistics cost. Most notable effect is observed when we consider the MC-Ramp echelon where the increase in the FCPS is steady and most dramatic.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δh^0_{ij}=-50%	24,522,528	10,689,632	2,533,140	823,518	5,390,174	4,816,468	269,597	-
Δh^0_{ij}=-25%	25,144,686	10,855,832	2,832,840	1,011,341	5,359,933	4,777,218	307,522	-
Baseline	25,402,749	10,686,480	2,660,735	1,647,580	5,320,570	4,814,520	272,864	-
Δh^0_{ij}=+25%	25,344,226	10,817,752	2,521,315	1,416,688	5,631,192	4,681,660	275,619	-
Δh^0_{ij}=+50%	25,626,923	10,847,709	2,521,315	1,760,460	5,574,699	4,662,250	260,490	-

Table 3.21. Effect of changing per Shipment Fixed Cost on Logistics Costs (All echelons).

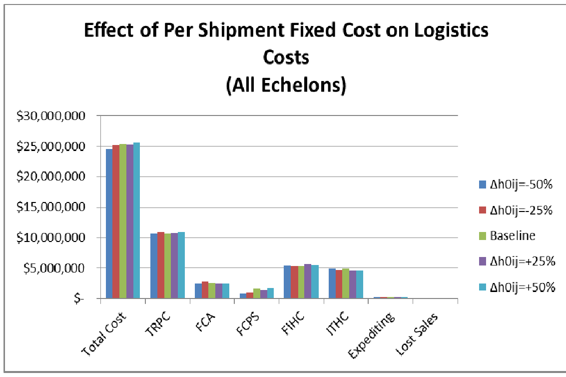
	PLANT-MC				MC-RAMP				FIHC		
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	PLANT	MC	RAMP
Δh^0_{ij}=-50%	6,758,049	853,706	893,500	463,113	3,931,583	3,962,762	1,639,640	360,405	690,444	157,045	4,542,685
Δh^0_{ij}=-25%	6,974,866	863,328	1,076,400	486,094	3,880,966	3,913,890	1,756,440	525,248	474,046	306,504	4,579,383
Baseline	6,784,274	855,565	1,025,400	921,450	3,902,206	3,958,955	1,635,335	726,130	209,967	467,569	4,643,034
Δh^0_{ij}=+25%	6,954,752	816,579	974,400	570,750	3,863,000	3,865,082	1,546,915	845,938	457,450	373,021	4,800,721
Δh^0_{ij}=+50%	6,961,545	808,847	974,400	723,863	3,886,164	3,853,404	1,546,915	1,036,598	477,830	483,622	4,613,247

Table 3.22. Effect of changing per Shipment Fixed Cost on Logistics Costs by echelon and facility.

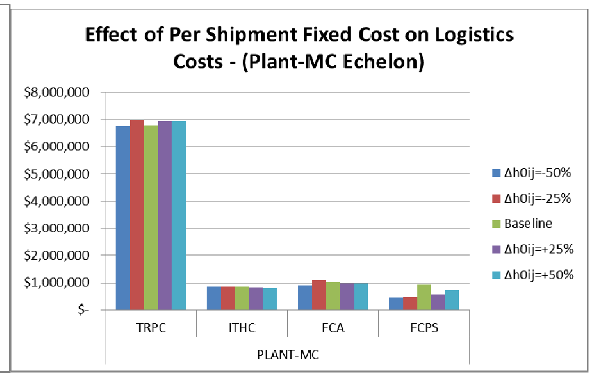
3.7.1.5 Effect of In-transit Inventory Holding Cost

The effect of changing the in-transit holding cost parameter is illustrated in Tables 3.23 and 3.24 as well as in Figure 3.11. Clearly the increasing in-transit holding cost parameter increases the total logistics cost. Most notable effect is observed when we consider the MC-Ramp echelon where the increase in the FCPS is steady and most dramatic.

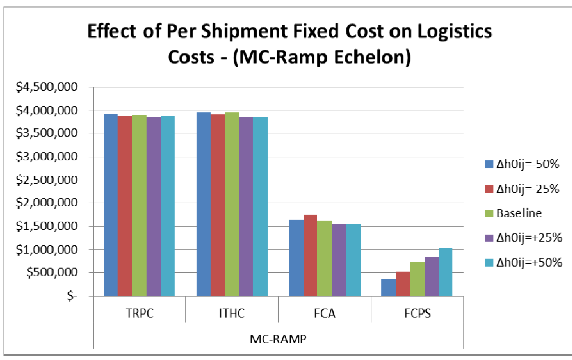
This is because the in-transit holding cost is a major component of the total cost in the MC-Ramp echelon given that the distances traveled are much higher than the distances between Plants and MCs.



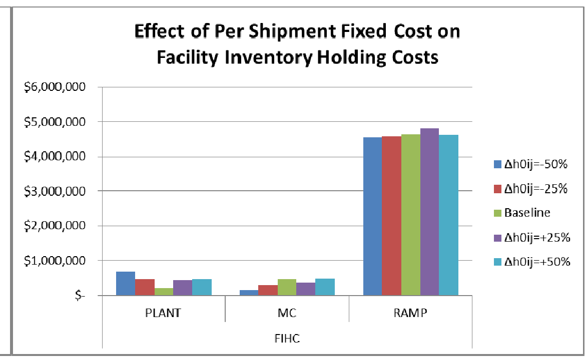
(a)



(b)



(c)



(d)

Figure 3.10. Effect of changing per Shipment Fixed Cost on Logistics Costs by type, echelon and facility type.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δpt^0_v=-30%	24,039,674	10,752,950	2,804,090	1,622,130	5,234,972	3,399,516	226,016	-
Δpt^0_v=-15%	24,445,733	10,698,173	2,735,340	1,361,855	5,383,291	4,036,601	230,474	-
Baseline	25,402,749	10,686,480	2,660,735	1,647,580	5,320,570	4,814,520	272,864	-
Δpt^0_v=+15%	25,849,382	10,802,833	2,682,240	1,305,815	5,588,382	5,268,688	201,423	-
Δpt^0_v=+30%	26,746,591	10,774,594	2,786,085	1,405,310	5,556,781	5,949,805	274,015	-

Table 3.23. Effect of changing In-transit Holding Cost on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				FIHC		
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	PLANT	MC	RAMP
Δpt^0_v=-30%	6,868,496	610,782	1,076,400	881,150	3,884,454	2,788,733	1,727,690	740,980	144,792	308,043	4,782,137
Δpt^0_v=-15%	6,871,033	709,386	1,025,400	663,600	3,827,139	3,327,215	1,709,940	698,255	368,252	28,225	4,986,814
Baseline	6,784,274	855,565	1,025,400	921,450	3,902,206	3,958,955	1,635,335	726,130	209,967	467,569	4,643,034
Δpt^0_v=+15%	6,904,816	919,821	1,076,400	582,425	3,898,017	4,348,868	1,605,840	723,390	282,712	257,681	5,047,989
Δpt^0_v=+30%	6,830,688	1,037,073	1,025,400	666,000	3,943,906	4,912,732	1,760,685	739,310	396,693	138,413	5,021,675

Table 3.24. Effect of changing t In-transit holding Cost on Logistics Costs by echelon and facility.

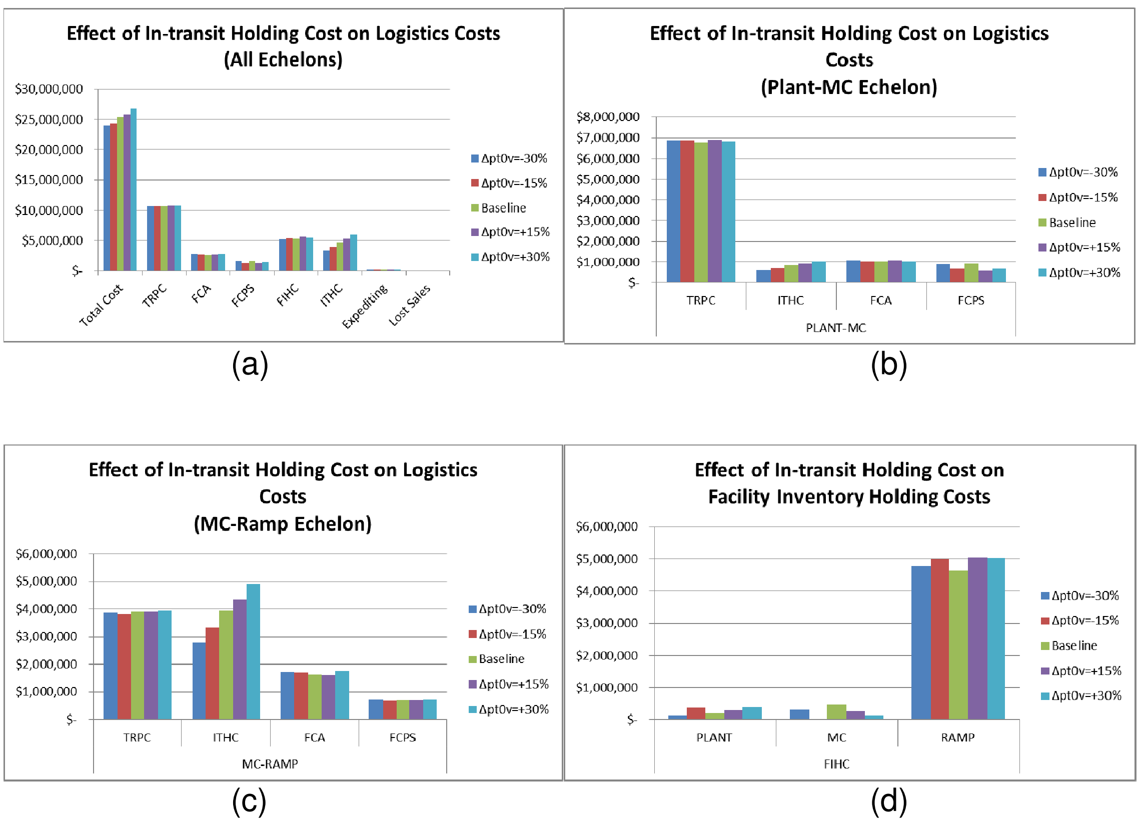


Figure 3.11. Effect of changing in-transit holding cost on Logistics Costs by type, echelon and facility type.

3.7.1.6 Effect of Facility Inventory Holding Cost

The effect of changing the facility inventory holding cost parameter is illustrated in Tables 3.25 and 3.26 as well as in Figure 3.12. The increasing holding cost parameter increases the total logistics cost linearly. Further, when the holding cost is cheapest, the expediting cost is least since there are more inventories at the ramps. Among the three facility types, the inventory holding cost at Plants are least affected, e.g. holding cost at plants is more robust. The effect of holding cost increases as we go downstream in the logistics system and the hodling cost of ramps are most sensitive. This is because the inventory is mostly placed in the downstream to avoid the lost sales and expediting.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δpf^0_{ij}=-30%	23,474,795	10,858,570	2,685,315	1,239,845	3,997,804	4,526,694	166,567	-
Δpf^0_{ij}=-15%	24,216,143	10,718,810	2,487,490	1,362,555	4,685,811	4,741,720	219,757	-
Baseline	25,402,749	10,686,480	2,660,735	1,647,580	5,320,570	4,814,520	272,864	-
Δpf^0_{ij}=+15%	26,255,548	10,777,757	2,715,340	1,527,175	6,227,330	4,726,329	281,617	-
Δpf^0_{ij}=+30%	26,927,521	10,600,210	2,605,260	1,634,345	7,022,576	4,821,058	244,072	-

Table 3.25. Effect of changing Facility Inventory Holding Cost on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				FIHC		
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	PLANT	MC	RAMP
Δpf^0_{ij}=-30%	6,929,658	793,966	974,400	521,100	3,928,911	3,732,728	1,710,915	718,745	260,815	157,592	3,579,397
Δpf^0_{ij}=-15%	6,884,724	831,347	1,025,400	670,725	3,834,086	3,910,374	1,462,090	691,830	228,716	441,179	4,015,916
Baseline	6,784,274	855,565	1,025,400	921,450	3,902,206	3,958,955	1,635,335	726,130	209,967	467,569	4,643,034
Δpf^0_{ij}=+15%	6,854,573	850,631	1,076,400	804,700	3,923,184	3,875,698	1,638,940	722,475	136,281	451,558	5,639,491
Δpf^0_{ij}=+30%	6,747,138	838,647	960,400	887,675	3,853,071	3,982,411	1,644,860	746,670	346,718	565,138	6,110,720

Table 3.26. Effect of changing Facility Inventory Holding Cost on Logistics Costs by echelon and facility.

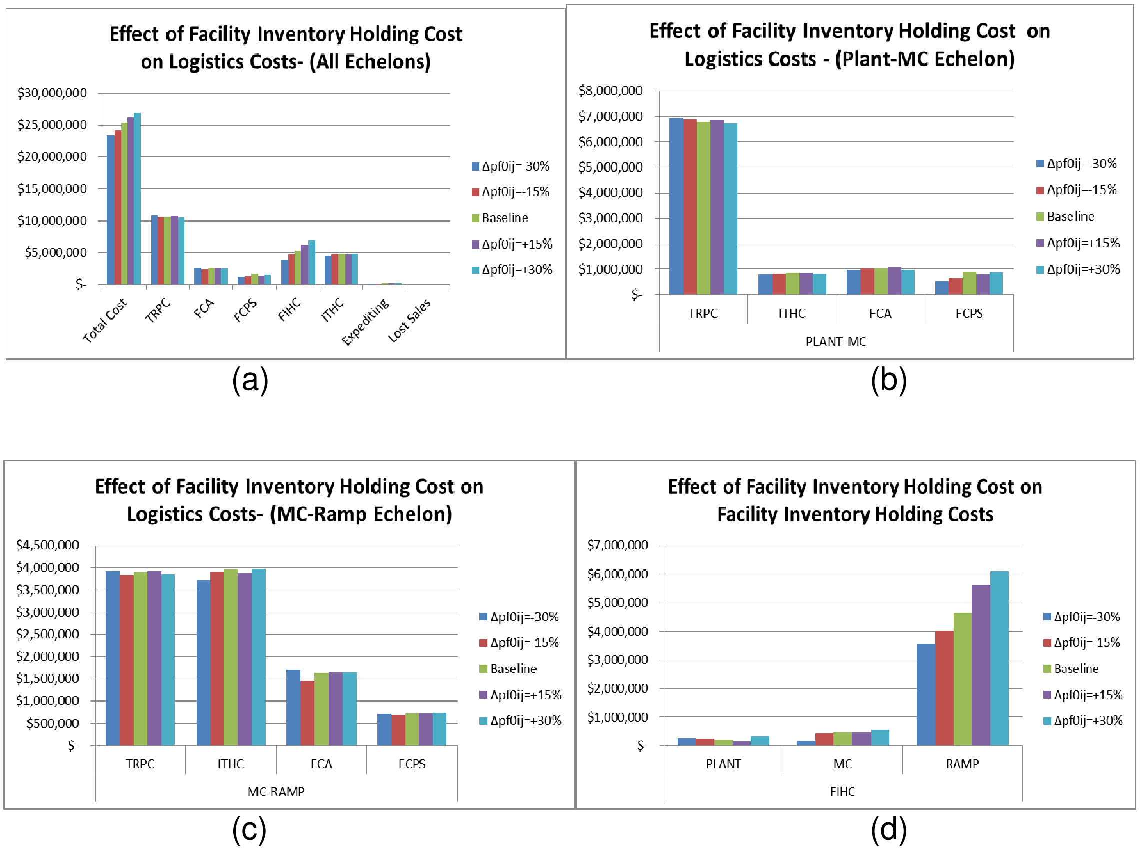


Figure 3.12. Effect of changing Facility Inventory Holding Cost on Logistics Costs by echelon and facility type.

3.7.1.7 Effect of Arc Fixed Cost

The effect of changing the arc fixed cost parameter is illustrated in Tables 3.27 and 3.28 as well as in Figure 3.13. The increasing fixed cost parameter increases the transportation cost, albeit slightly. This increase is due to the balancing between variable and fixed components of using transportation lanes. Further, increased fixed cost of arc selection forces using fewer arcs and hence one would expect to ship more frequently on those selected arcs due to the capacity constraint on the shipment size for each arc. However, we observe a a result countering this intuition where the FCPS is decreasing. In terms of the echelons, the increasing fixed cost of arc selection affects the two echelons similarly.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δf^0_{ij}=-50%	23,896,132	10,684,141	1,356,120	1,475,070	5,421,955	4,702,149	256,697	-
Δf^0_{ij}=-25%	25,018,772	10,702,123	1,876,511	1,551,425	5,976,256	4,705,705	206,752	-
Baseline	25,402,749	10,686,480	2,660,735	1,647,580	5,320,570	4,814,520	272,864	-
Δf^0_{ij}=+25%	25,970,298	10,864,862	3,273,263	1,394,040	5,548,783	4,656,437	232,913	-
Δf^0_{ij}=+50%	26,594,364	10,812,371	3,963,015	1,320,810	5,714,588	4,497,401	286,178	-

Table 3.27. Effect of changing Arc fixed cost on logistics costs (All echelons).

	PLANT-MC				MC-RAMP				FIHC		
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	PLANT	MC	RAMP
Δf^0_{ij}=-50%	6,820,701	818,871	512,700	737,000	3,863,440	3,883,278	843,420	738,070	501,871	87,595	4,832,489
Δf^0_{ij}=-25%	6,808,943	841,422	769,050	871,475	3,893,180	3,864,283	1,107,461	679,950	214,296	412,384	5,349,576
Baseline	6,784,274	855,565	1,025,400	921,450	3,902,206	3,958,955	1,635,335	726,130	209,967	467,569	4,643,034
Δf^0_{ij}=+25%	6,850,438	801,466	1,198,125	663,425	4,014,424	3,854,971	2,075,138	730,615	719,410	99,242	4,730,131
Δf^0_{ij}=+50%	6,811,484	776,305	1,437,750	579,250	4,000,888	3,721,096	2,525,265	741,560	555,246	40,745	5,118,597

Table 3.28. Effect of changing Arc fixed cost on Logistics Costs by echelon and facility.

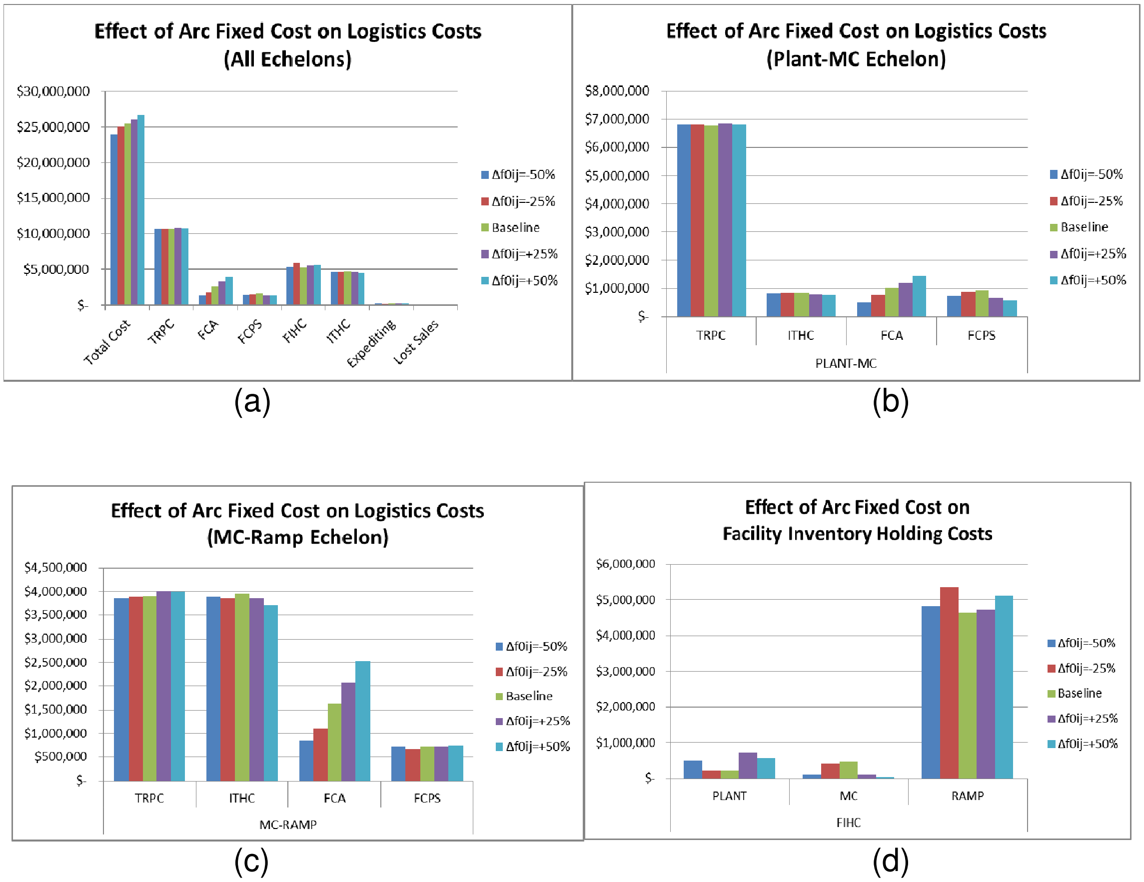


Figure 3.13. Effect of changing Arc fixed cost on the Logistics Costs by type, echelon and facility type.

3.7.1.8 Effect of Arc Capacity

The effect of changing the arc fixed cost parameter is illustrated in Tables 3.29 and 3.30 as well as in Figure 3.14. By reducing the arc capacities, the losgistics system become more constrained hence the overall system level cost increases, albeit slightly. This is a result of the over capacity in the baseline scenario (e.g., there is no cost decrease between the +10% and +20% scenario).There are three observations with this sensitivity analysis. First, the transportation cost increases with reduced arc transportation capacity. Second the fixed cost of selecting arcs increase as more and more arcs are being used. This is especially more apparent for the Plant-MC echelon than the MC-Ramp echelon. Third, the fixed cost per shipment increases as one way of using the arcs that are preferable (e.g. lower variable transportation cost and fixed costs) under more restrictive capacity is to increase the frequency of shipments.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δu^0_{ij}=-20%	26,280,986	10,910,570	3,037,335	1,956,120	5,328,880	4,839,208	208,873	-
Δu^0_{ij}=-10%	25,768,440	10,978,743	2,936,760	1,435,315	5,568,234	4,578,673	270,716	-
Baseline	25,402,749	10,686,480	2,660,735	1,647,580	5,320,570	4,814,520	272,864	-
Δu^0_{ij}=+10%	24,555,927	10,807,455	2,049,115	1,139,440	5,895,443	4,372,350	292,124	-
Δu^0_{ij}=+20%	24,567,590	10,497,152	2,001,845	1,476,965	5,324,308	5,012,592	254,728	-

Table 3.29. Effect of changing Arc capacities on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				FIHC		
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	PLANT	MC	RAMP
Δu^0_{ij}=-20%	6,889,000	876,460	1,146,450	1,095,050	4,021,571	3,962,748	1,890,885	861,070	372,106	273,463	4,683,311
Δu^0_{ij}=-10%	6,897,498	806,175	1,146,450	647,900	4,081,244	3,772,498	1,790,310	787,415	392,900	355,268	4,820,066
Baseline	6,784,274	855,565	1,025,400	921,450	3,902,206	3,958,955	1,635,335	726,130	209,967	467,569	4,643,034
Δu^0_{ij}=+10%	6,808,269	729,626	633,600	477,400	3,999,186	3,642,724	1,415,515	662,040	830,926	252,626	4,811,891
Δu^0_{ij}=+20%	6,782,579	883,290	627,700	883,700	3,714,573	4,129,302	1,374,145	593,265	622,053	255,131	4,447,124

Table 3.30. Effect of changing arc capacities on Logistics Costs by echelon and facility.

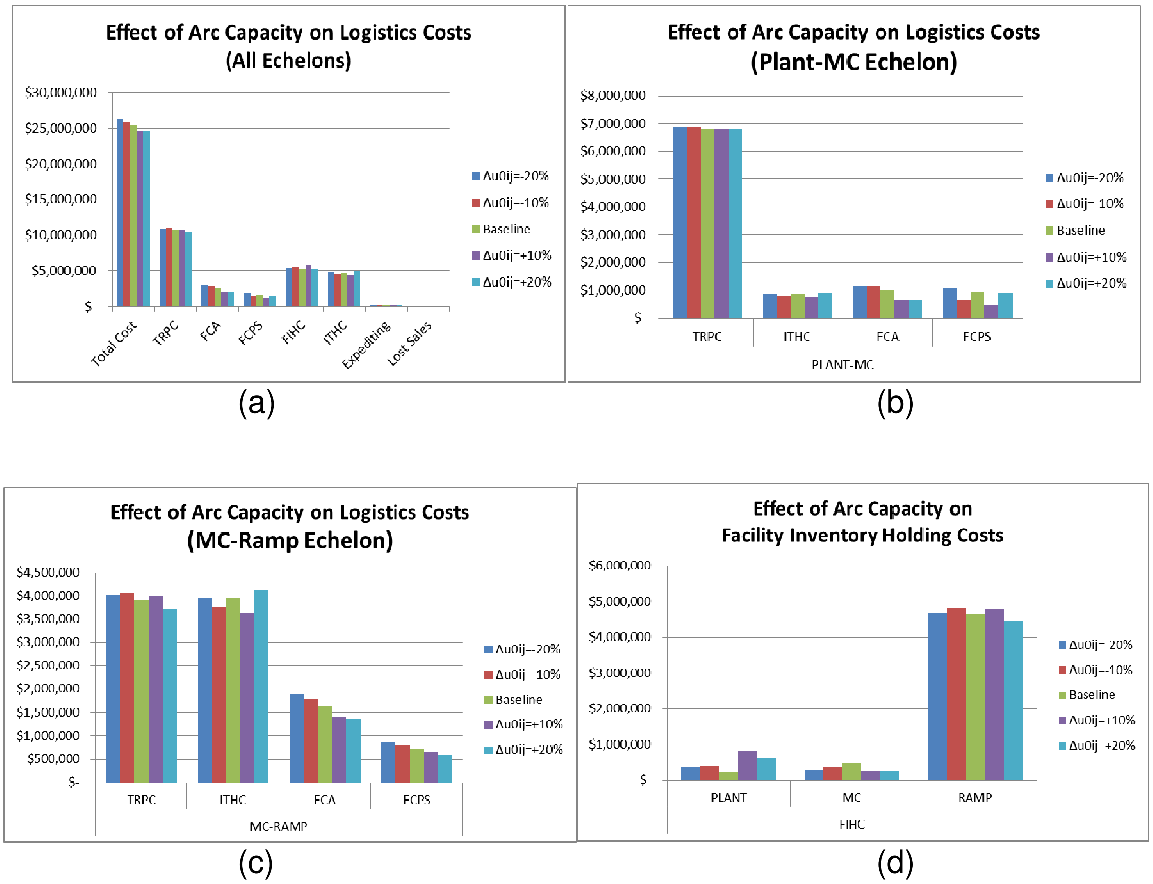


Figure 3.14. Effect of changing Arc Capacities on Logistics Costs by type, echelon and facility type.

3.7.2 With Collaboration

In this section, we will compare the different performance parameters of the Outbound Logistics Network system where there is collaboration.

3.7.2.1 Baseline Scenario

As in the preceding subsection, we first discuss the baseline scenario under collaboration. The summary of variable transportation costs is summarized as below by echelon, by product and by period. While the demand for Product 1 is more than Product 2, the variable cost of transportation per unit Product 2 is higher than Product 1, thus their period costs are similar in both P-M but different in the M-R echelons as there are more frequent deliveries in the M-R echelons. Compared to the no collaboration case the P-M echelon has slightly higher cost as do the M-R echelon. Further there is about 300K transportation cost due to the collaboration between plants. Hence total transportation variable cost is higher in baseline collaboration compared to the no collaboration case.

P-M	Product 1	Product 2	Total	M-R	Product 1	Product 2	Total
Period 1	1,161,987	1,140,111	**2,302,098**	**Period 1**	611,504	662,519	**1,274,022**
Period 2	1,066,891	1,103,109	**2,170,000**	**Period 2**	626,151	728,988	**1,355,139**
Period 3	1,219,456	1,205,401	**2,424,858**	**Period 3**	603,979	674,511	**1,278,490**
Total	**3,448,334**	**3,448,621**	**6,896,955**	**Total**	**1,841,633**	**2,066,018**	**3,907,651**

P-P	Product 1	Product 2	Total
Period 1	23,062	7,091	**30,152**
Period 2	0	1,074	**1,074**
Period 3	2,054	23,501	**25,555**
Total	**124,947**	**178,388**	**303,335**

Table 3.31. Total Variable Transportation Cost by echelon, product and period.

Next table illustrates total fixed cost of selecting arcs within each echelon by period as well total fixed cost of shipments by period. Results, when compared with the no collaboration, show that the total fixed cost of using arcs is lesser with collaboration than the no collaboration case. The fixed cost of using an arc with collaboration in the P-M echelon is $716,400 vs. $1,025,400 without collaboration. Similarly, the fixed cost of using an arc with collaboration in the M-R echelon is $1,546,915 vs. $1,635,335 without collaboration. This is because by transshipping between the facilities, there are fewer “preferable” arcs selected thus reducing the total fixed cost of arc selection. Further, the collaboration allows consolidation of shipments from plants to mixing centers. This is observed from the P-M total per shipment fixed costs which is about one third in the collaboration case ($331,075) of that in the no collaboration case ($921,450). The cost of this consolidation opportunity is about 25K which is much less than the savings achieved.

	P-M		M-R		P-P	
Fixed Cost Arc	**Period 1**	261,100	**Period 1**	462,750	**Period 1**	30,750
	Period 2	194,200	**Period 2**	537,570	**Period 2**	21,200
	Period 3	261,100	**Period 3**	546,595	**Period 3**	30,750
	Total	**716,400**	**Total**	**1,546,915**	**Total**	**82,700**
Fixed Cost Per Shipment	**Period 1**	113,025	**Period 1**	205,840	**Period 1**	10,945
	Period 2	106,750	**Period 2**	265,550	**Period 2**	1,545
	Period 3	111,300	**Period 3**	228,755	**Period 3**	13,405
	Total	**331,075**	**Total**	**700,145**	**Total**	**25,895**

Table 3.32. Fixed Transportation Cost by echelon and period.

The next table summarizes the inventory holding cost for the baseline scenario. The inventory holding cost at the plant with collaboration ($256,757) is higher than the inventory holding cost without collaboration (($209,967) due to the fact that inventories are consolidated at the plant.

However, the inventory holding cost at the mixing center is less with collaboration ($368,892) than without collaboration ($467,569) as Mixing Centers since they are transshipment points and has access to most inflow and outflow arcs. In contrast, the plants have only access to the mixing centers. The ramps on the other hand have higher level of inventory with collaboration due to the fact that shortages lead to expediting and lost sales. Hence, the inventory holding cost at the ramp with collaboration ($4,953,753) is higher than the no collaboration case (4,643,034). In fact, the inventory levels are balanced between the expediting/lost sale cost and inventory holding.In comparison with the no collaboration case, we notice that the inventory cost at the Plants and Ramps are higher whereas the mixing center inventory is lesser.

	Plant			MC			Ramp		
	Product 1	**Product 2**	**Total**	**Product 1**	**Product 2**	**Total**	**Product 1**	**Product 2**	**Total**
Period 1	0	137,227	**137,227**	140,050	145,016	**285,066**	1,919,114	2,136,265	**4,055,379**
Period 2	0	0	**0**	0	0	**0**	79,073	19,200	**98,273**
Period 3	24,876	94,654	**119,530**	28,515	55,311	**83,826**	356,770	443,331	**800,101**
Total	**24,876**	**231,881**	**256,757**	**168,565**	**200,327**	**368,892**	**2,354,957**	**2,598,796**	**4,953,753**

Table 3.33. Inventory Holding Cost by facility, product, and period.

Overall, in comparison with the no collaboration case, collaboration provides benefits, primarily in the fixed component of transportation costs (arc selection and per shipment costs).

3.7.2.2 Effect of Variable Transportation Cost

In what follows, we investigate the effect of changing cost parameters on the logistics system costs by type of cost, echelon, and facility. We first consider the effect of transportation cost parameter change on the logistics system performance. The results are displayed in Tables 3.34, 3.35, 3.36 and Figure 3.15 and 3.16.

It is clear that for increasing transportation cost increases the total cost and decreasing the transportation cost decreases total cost. The other cost doesn't change significantly for changing the transportation cost. There is a linear relation between the transportation cost and the total cost. The transportation cost change impacts the P-M echelon more than the M-R and P-P echelon.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δc^0_{ijv}=-20%	22,475,502	8,678,194	2,381,115	1,104,695	5,393,193	4,660,724	257,580	-
Baseline	24,672,205	10,861,388	2,346,015	1,057,115	5,579,396	4,555,997	272,294	-
Δc^0_{ijv}=+20%	26,951,305	13,036,667	2,491,440	1,114,785	5,363,943	4,682,388	262,081	-

Table 3.34. Effect of changing Transportation Cost on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				PLANT-PLANT			
Scenarios	**TRPC**	**ITHC**	**FCA**	**FCPS**	**TRPC**	**ITHC**	**FCA**	**FCPS**	**TRPC**	**ITHC**	**FCA**	**FCPS**
Δc^0_{ijv}=-20%	5,474,544	740,655	783,300	351,800	3,132,650	3,890,513	1,525,315	711,060	71,000	740,655	72,500	41,835
Baseline	6,896,955	765,736	716,400	331,075	3,907,651	3,773,693	1,546,915	700,145	56,781	765,736	82,700	25,895
Δc^0_{ijv}=+20%	8,294,781	772,919	783,300	365,450	4,690,373	3,894,445	1,641,140	726,915	51,513	772,919	67,000	22,420

Table 3.35. Effect of changing Transportation Cost on Logistics Costs by echelon.

	FIHC		
Scenarios	**PLANT**	**MC**	**RAMP**
Δc^0_{ijv}=-20%	516,372	230,543	4,646,285
Baseline	256,757	368,892	4,953,753
Δc^0_{ijv}=+20%	655,480	6,053	4,702,416

Table 3.36. Effect of changing Transportation Cost on Inventory Holding Cost by each facility.

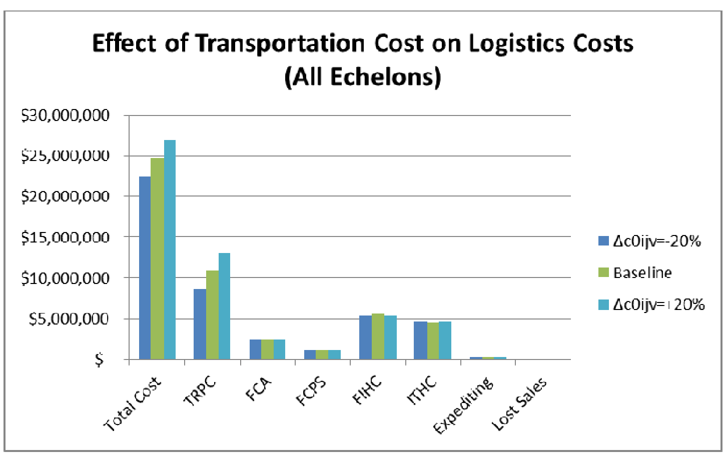
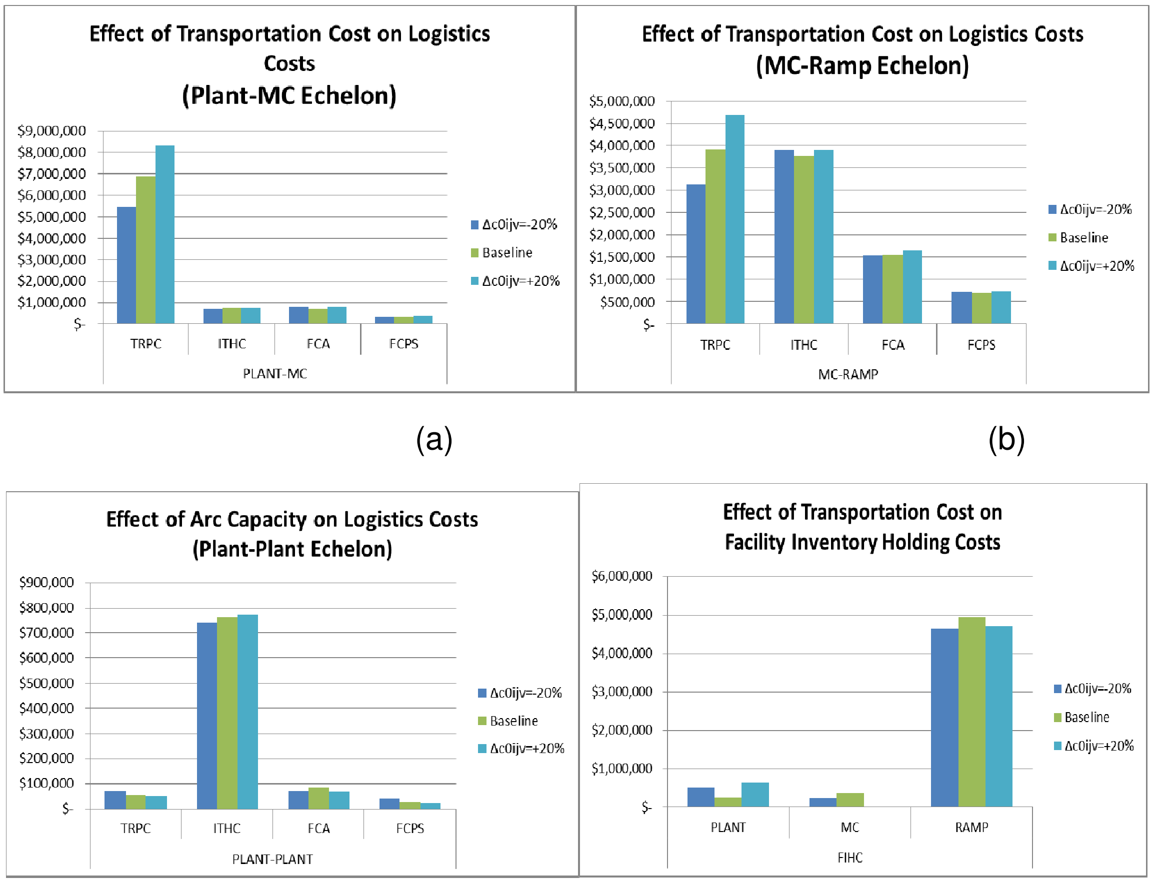


Figure 3.15. Effect of changing Transportation Cost on Logistics Costs.



(c) (d)

Figure 3.16. Effect of changing Transportation Cost on Logistics Costs by echelon and facility type.

3.7.2.3 Effect of Service Level at Ramps

The results in Table 3.37 show the effect of service level on the cost elements of the entire logistics system (e.g. all echelons). As the service level incresaes, the total cost incresaes more for the collaboration case than the non-collaboration. This is because increasing service level means increasing inventory level thus making the total cost increase. Also, service level incresae increases the FIHC cost for the collaboration case than the non-collaboration.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
SL=1.0	32,294,664	10,810,567	2,275,145	1,047,120	13,298,205	4,863,627	-	-
Baseline (SL^0=0.7)	24,672,205	10,861,388	2,346,015	1,057,115	5,579,396	4,555,997	272,294	-
SL=0.6	24,805,196	10,754,444	2,388,090	1,319,170	5,489,268	4,642,346	211,878	-

Table 3.37. Effect of changing Ramp Service Level on Logistics Costs (All echelons).

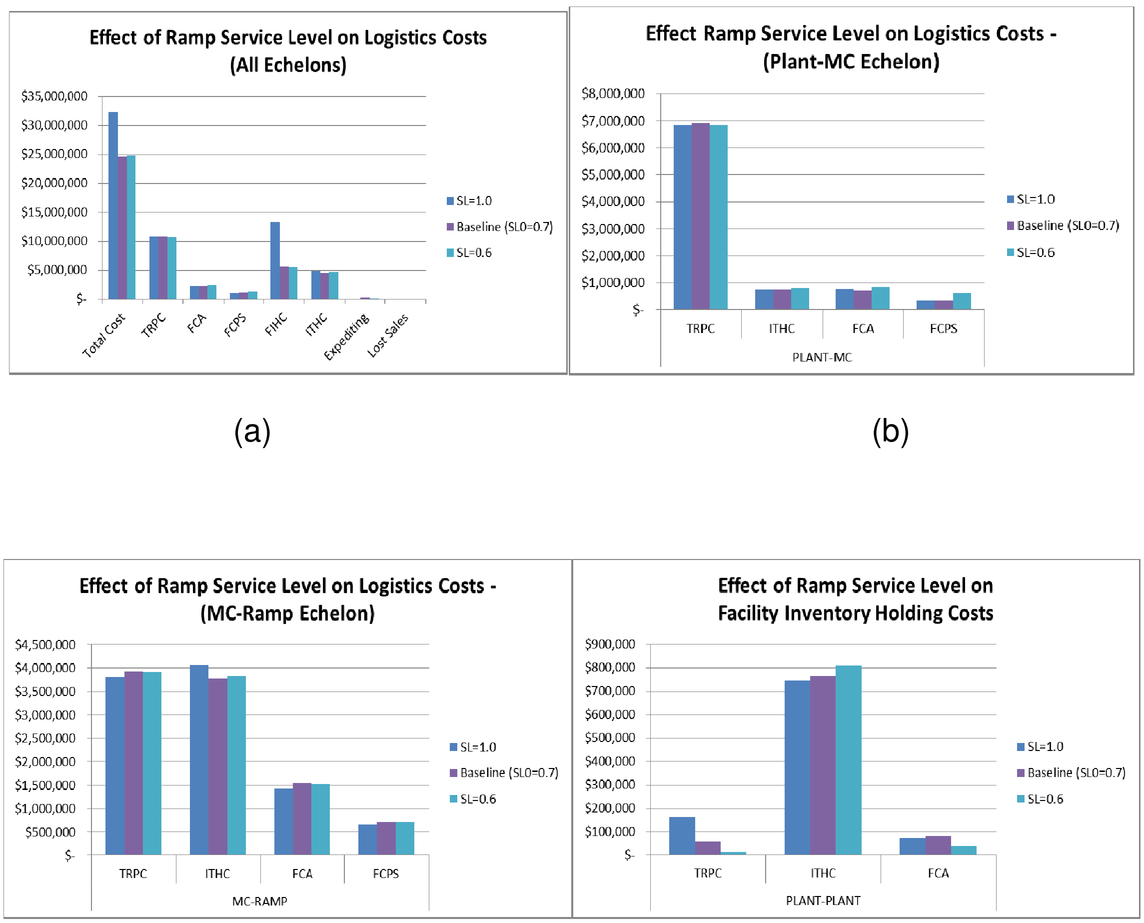
When we analyze the effect of changing the service level in each echelon, we see differences between echelons. Similar to non-collaboration, increasing service level impacts the logistics cost in the M-R echelon with collaboration. Last observation is for the inventory hodling cost at the facilities (FIHC). We observe that as we go upstream in the logistics network, the increasing service level increases the inventory levels more dramatically. This is true for both collaboration and non-collaboration scenarios.

	PLANT-MC				MC-RAMP				PLANT-PLANT			
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS
SL=1.0	6,854,705	745,913	788,350	327,375	3,791,474	4,060,178	1,412,045	649,495	164,389	745,913	74,750	70,250
Baseline (SL^0=0.7)	6,896,955	765,736	716,400	331,075	3,907,651	3,773,693	1,546,915	700,145	56,781	765,736	82,700	25,895
SL=0.6	6,847,870	808,126	834,300	609,800	3,893,400	3,831,720	1,514,290	706,895	13,174	808,126	39,500	2,475

Table 3.38. Effect of changing Ramp Service Level on Logistics Costs by echelon.

	FIHC		
Scenarios	**PLANT**	**MC**	**RAMP**
SL=1.0	3,152,082	1,613,290	8,532,842
Baseline (SL^0=0.7)	256,757	368,892	4,953,753
SL=0.6	397,301	182,639	4,909,334

Table 3.39. Effect of changing Ramp Service Level on Inventory Holding Cost by each facility.



(a) (b)

(c) (d)

Figure 3.17. Effect of changing Ramp Service Level on Logistics Costs by echelon and facility type

3.7.2.4 Effect of Per Shipment Fixed Cost

The effect of changing the per shipment fixed cost parameter is illustrated in Tables 3.40, 3.41, and 3.42 as well as in Figure 3.19 and 3.20. Clearly the increasing per shipment fixed cost increases the total logistics cost. Changing per shipment fixed cost increases the in-house inventory cost at the plant.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δh^0_{ij}=-50%	24,072,312	10,611,897	2,290,715	755,848	5,459,266	4,725,173	229,413	-
Baseline	24,672,205	10,861,388	2,346,015	1,057,115	5,579,396	4,555,997	272,294	-
Δh^0_{ij}=+50%	25,166,922	10,855,592	2,386,215	1,605,510	5,451,070	4,607,678	260,857	-

Table 3.40. Effect of changing per Shipment Fixed Cost on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				PLANT-PLANT			
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS
Δh^0_{ij}=-50%	6,724,181	823,955	753,400	415,025	3,868,007	3,897,423	1,476,615	338,040	19,710	823,955	60,700	2,783
Baseline	6,896,955	765,736	716,400	331,075	3,907,651	3,773,693	1,546,915	700,145	56,781	765,736	82,700	25,895
Δh^0_{ij}=+50%	6,890,941	762,897	783,300	548,700	3,900,062	3,824,236	1,546,915	1,023,577	64,589	762,897	56,000	33,233

Table 3.41. Effect of changing per Shipment Fixed Cost on Logistics Costs by echelon

	FIHC		
Scenarios	PLANT	MC	RAMP
Δh^0_{ij}=-50%	409,398	190,308	4,859,568
Baseline	256,757	368,892	4,953,753
Δh^0_{ij}=+50%	463,811	214,155	4,773,111

Table 3.42. Effect of changing per Shipment Fixed Cost on Inventory Holding Cost by each facility

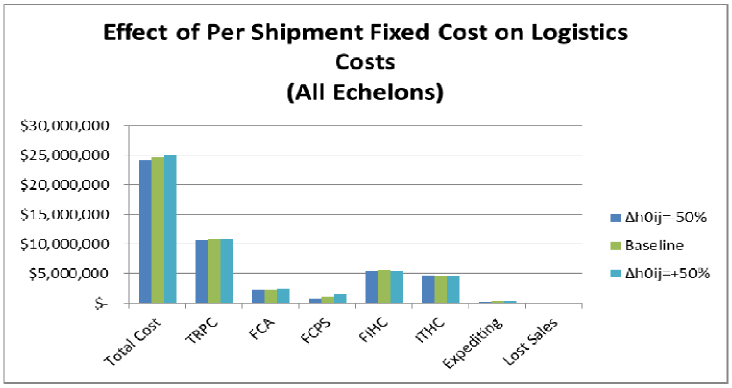
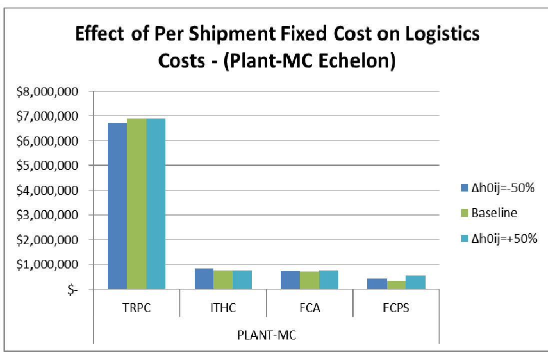
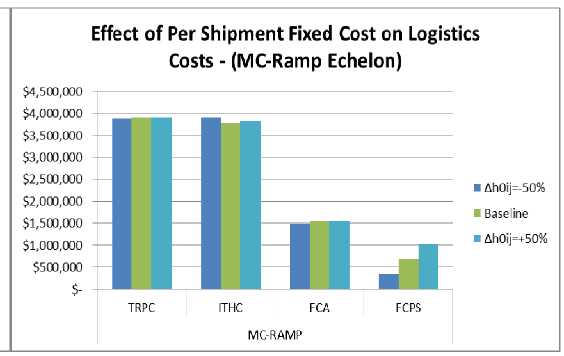


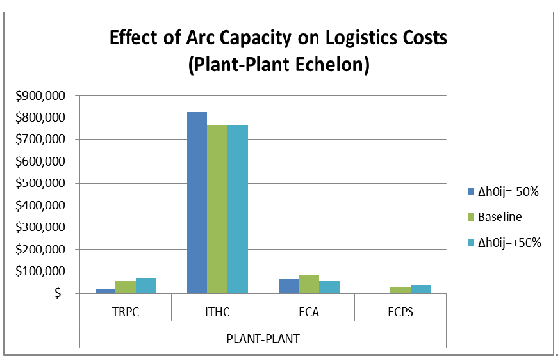
Figure 3.18. Effect of changing per Shipment Fixed Cost on Logistics Cost



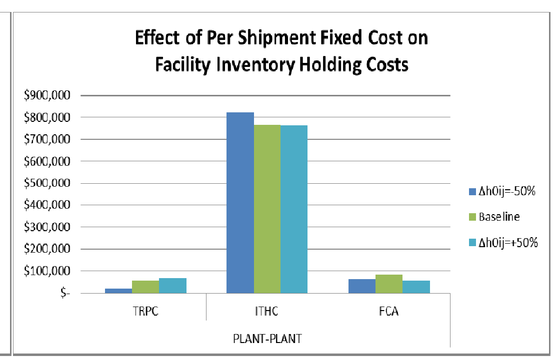
(a)



(b)



(c)



(d)

Figure 3.19. Effect of changing per Shipment Fixed Cost on Logistics Costs by echelon and facility type.

3.7.2.5 Effect of In-transit Inventory Holding Cost

The effect of changing the in-transit holding cost parameter is illustrated in Tables 3.43 and 3.44, and 3.45 as well as in Figure 3.20 and 3.21.

Clearly the increasing in-transit holding cost parameter increases the total logistics cost. Most notable effect is observed when we consider the MC-Ramp echelon where the increase in the FCPS is steady and most dramatic. This is because the in-transit holding cost is a major component of the total cost in the MC-Ramp echelon given that the distances traveled are much higher than the distances between Plants and MCs.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δpt^0_v=-30%	23,266,459	10,892,479	2,263,440	1,041,515	5,411,248	3,423,991	233,787	-
Baseline	24,672,205	10,861,388	2,346,015	1,057,115	5,579,396	4,555,997	272,294	-
Δpt^0_v=+30%	26,116,165	10,865,471	2,458,660	1,113,805	5,720,630	5,748,473	209,125	-

Table 3.43. Effect of changing In-transit Holding Cost on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				PLANT-PLANT			
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS
Δpt^0_v=-30%	6,948,181	552,758	718,300	320,600	3,814,985	2,841,616	1,467,140	661,020	129,313	552,758	78,000	59,895
Baseline	6,896,955	765,736	716,400	331,075	3,907,651	3,773,693	1,546,915	700,145	56,781	765,736	82,700	25,895
Δpt^0_v=+30%	6,846,457	964,342	853,350	358,500	3,985,582	4,770,354	1,574,560	739,440	33,433	964,342	30,750	15,865

Table 3.44. Effect of changing the In-transit Holding Cost on Logistics Costs by echelon.

	FIHC		
Scenarios	PLANT	MC	RAMP
Δpt^0_v=-30%	274,004	323,280	4,813,972
Baseline	256,757	368,892	4,953,753
Δpt^0_v=+30%	661,402	95,132	4,964,101

Table 3.45. Effect of changing In-transit Holding Cost on Inventory Holding cost by each facility

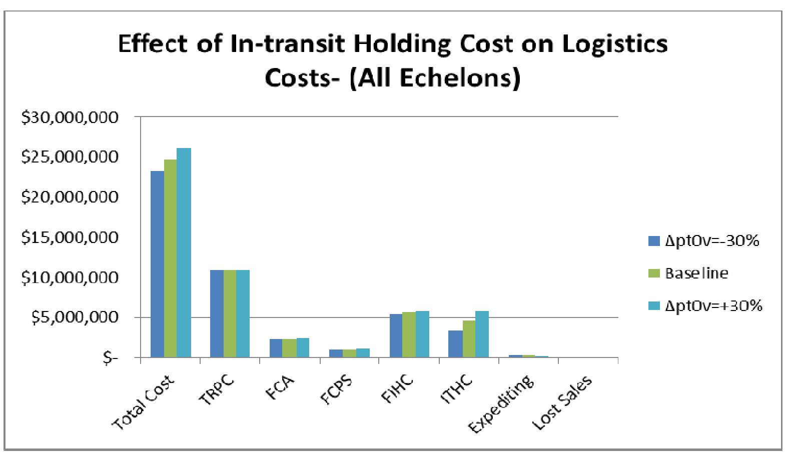


Figure 3.20. Effect of changing the In-transit Holding Cost on Logistics Costs.

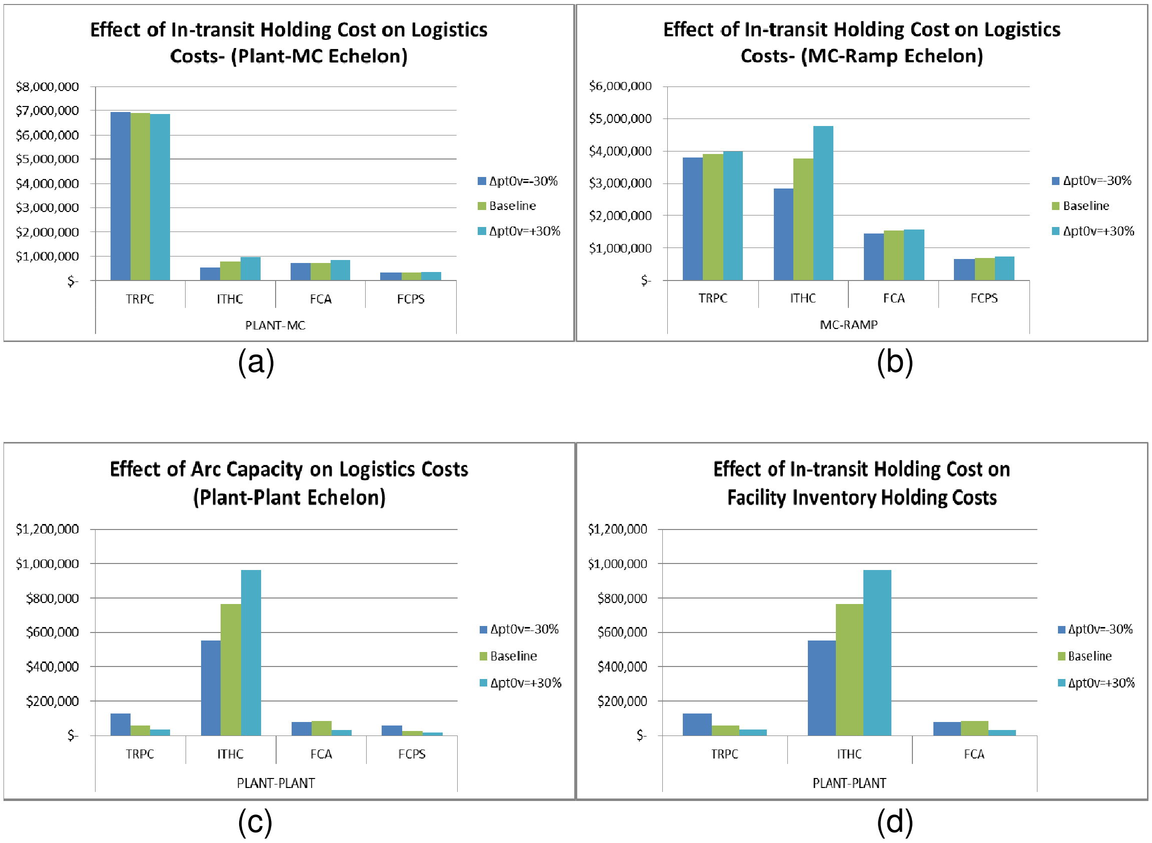


Figure 3.21. Effect of changing In-transit Holding Cost on Logistics Costs by echelon and facility type.

3.7.2.6 Effect of Facility Inventory Holding Cost

The effect of changing the facility inventory holding cost parameter is illustrated in Tables 3.46, 3.47 and 3.48 as well as in Figure 3.22 and 3.23. The increasing holding cost parameter increases the total logistics cost linearly. Further, when the holding cost is cheapest, the expediting cost is least since there are more inventories at the ramps. Among the three facility types, the inventory holding cost at Plants are least affected, e.g. holding cost at plants is more robust. The effect of holding cost increases as we go downstream in the logistics system and the hodling cost of ramps are most sensitive. This is because the inventory is mostly placed in the downstream to avoid the lost sales and expediting.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δpf^0_{ij}=-30%	22,955,359	10,858,102	2,363,115	1,055,075	4,032,957	4,528,352	117,758	-
Baseline	24,672,205	10,861,388	2,346,015	1,057,115	5,579,396	4,555,997	272,294	-
Δpf^0_{ij}=+30%	26,322,668	10,746,634	2,375,015	1,291,090	6,940,541	4,711,581	257,808	-

Table 3.46. Effect of changing facility inventory holding cost parameter on logistics costs (All echelons).

	PLANT-MC				MC-RAMP				PLANT-PLANT			
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS
Δpf^0_{ij}=-30%	6,885,237	760,274	783,300	345,000	3,921,779	3,751,781	1,523,815	685,460	51,087	760,274	56,000	24,615
Baseline	6,896,955	765,736	716,400	331,075	3,907,651	3,773,693	1,546,915	700,145	56,781	765,736	82,700	25,895
Δpf^0_{ij}=+30%	6,863,206	815,309	767,400	578,675	3,863,822	3,892,044	1,546,915	705,480	19,606	815,309	60,700	6,935

Table 3.47. Effect of changing the facility inventory holding cost parameter on logistics costs by echelon.

	FIHC		
Scenarios	PLANT	MC	RAMP
Δpf^0_{ij}=-30%	296,660	157,360	3,578,945
Baseline	256,757	368,892	4,953,753
Δpf^0_{ij}=+30%	611,203	296,706	6,032,638

Table 3.48. Effect of changing the facility inventory holding cost parameter on inventory holding cost by each facility.

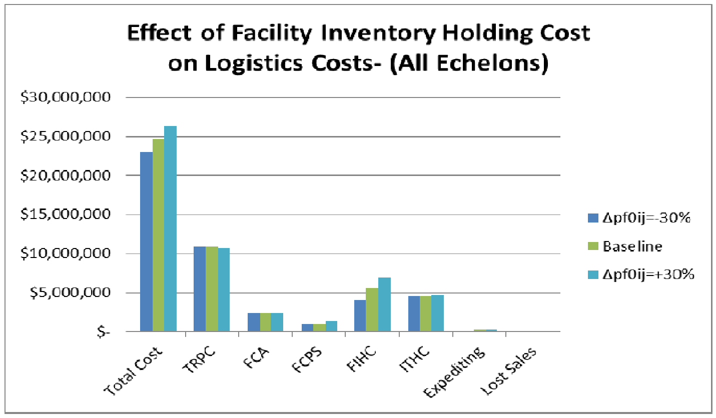


Figure 3.22. Effect of changing Facility Inventory Holding Cost on Logistics Costs

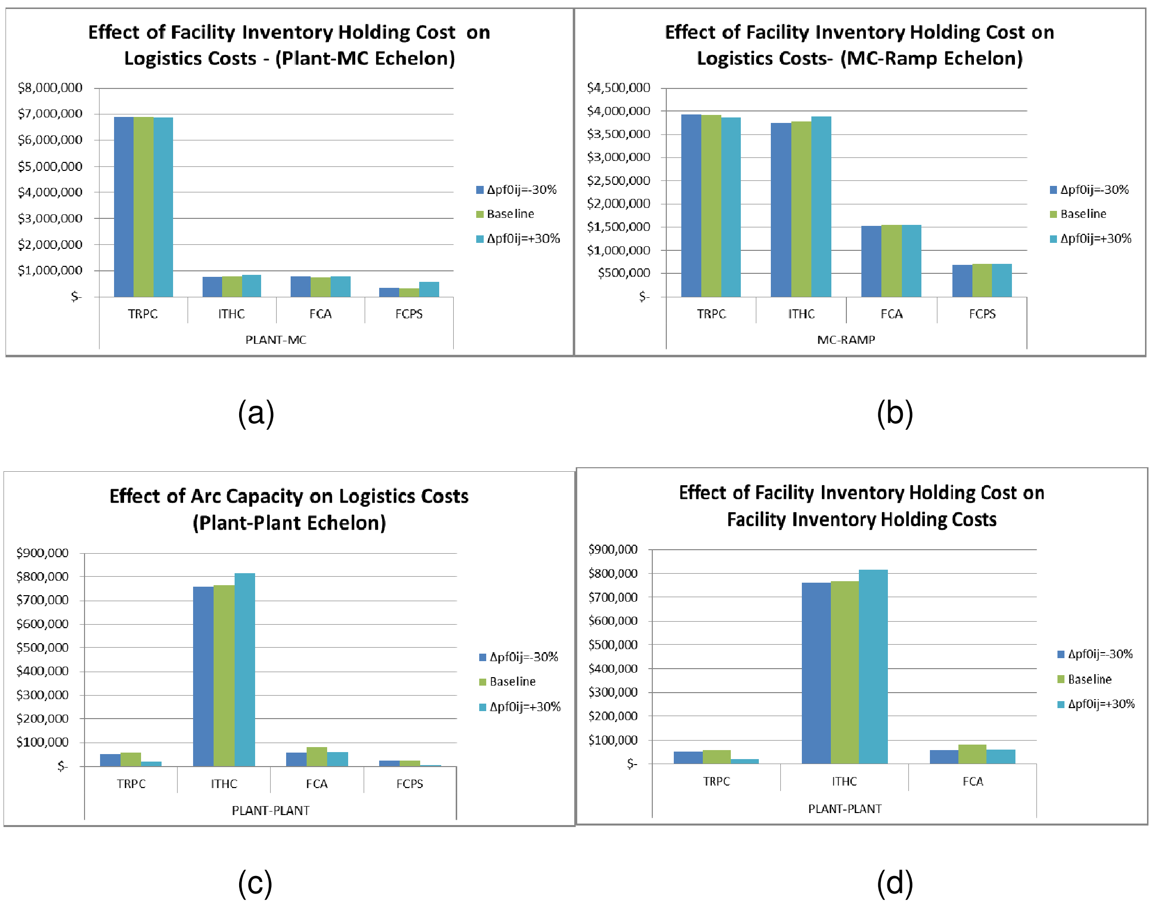


Figure 3.23. Effect of changing Facility Inventory Holding Cost on Logistics Costs

by echelon and facility type

3.7.2.7 Effect of Arc Fixed Cost

The effect of changing the arc fixed cost parameter is illustrated in Tables 3.49, 3.50 and 3.51 as well as in Figure 3.24 and 3.25.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
$\Delta f^0_{ij}=-50\%$	23,534,657	10,836,243	1,285,355	1,111,055	5,354,860	4,668,180	278,963	-
Baseline	24,672,205	10,861,388	2,346,015	1,057,115	5,579,396	4,555,997	272,294	-
$\Delta f^0_{ij}=+50\%$	25,852,667	10,929,853	3,343,485	1,177,755	5,512,103	4,657,017	232,455	-

Table 3.49. Effect of changing arc Fixed Cost on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				PLANT-PLANT			
Scenarios	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS	TRPC	ITHC	FCA	FCPS
$\Delta f^0_{ij}=-50\%$	6,905,163	769,507	426,675	365,075	3,848,209	3,871,645	822,430	706,605	82,871	769,507	36,250	39,375
Baseline	6,896,955	765,736	716,400	331,075	3,907,651	3,773,693	1,546,915	700,145	56,781	765,736	82,700	25,895
$\Delta f^0_{ij}=+50\%$	6,858,634	788,700	1,050,750	481,950	4,041,678	3,862,578	2,178,323	688,145	29,541	788,700	114,413	7,660

Table 3.50. Effect of changing the Arc Fixed Cost on Logistics Costs by echelon.

	FIHC		
Scenarios	PLANT	MC	RAMP
$\Delta f^0_{ij}=-50\%$	528,047	77,857	4,748,961
Baseline	256,757	368,892	4,953,753
$\Delta f^0_{ij}=+50\%$	305,407	284,327	4,922,376

Table 3.51. Effect of changing Facility Inventory Holding Cost on Inventory Holding Cost by each facility.

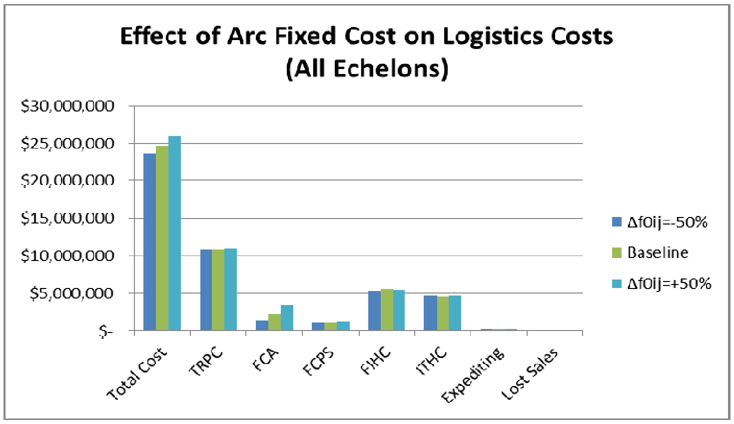
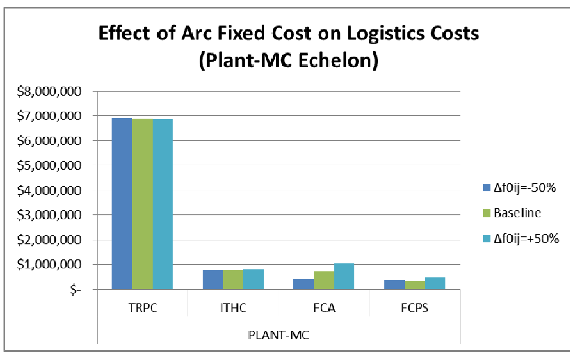
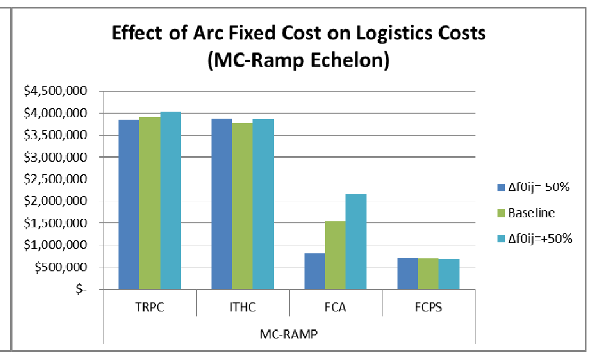


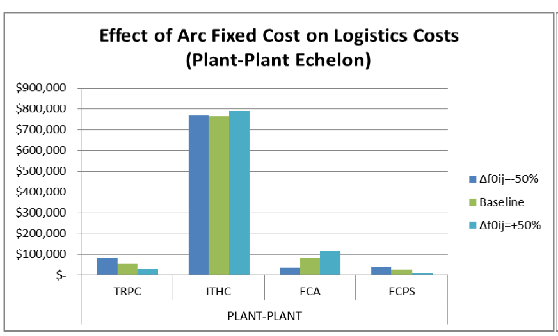
Figure 3.24. Effect of changing arc Fixed Cost on Logistics Costs



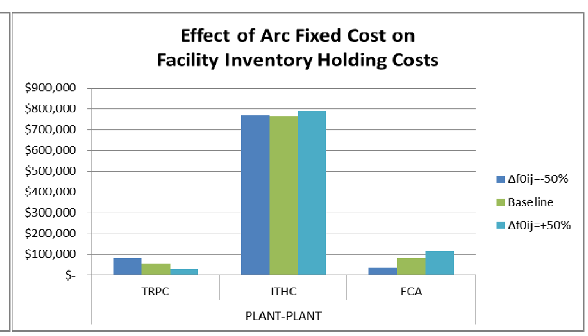
(a)



(b)



(c)



(d)

Figure 3.25. Effect of changing Arc Fixed Cost on Logistics Costs by echelon and facility type

The increasing fixed cost parameter increases the transportation cost, albeit slightly. This increase is due to the balancing between variable and fixed components of using transportation lanes. Further, increased fixed cost of arc selection forces using fewer arcs and hence one would expect to ship more frequently on those selected arcs due to the capacity constraint on the shipment size for each arc. However, we observe a result countering this intuition where the FCPS is decreasing. In terms of the echelons, the increasing fixed cost of arc selection affects the two echelons similarly.

3.7.2.8 Effect of Arc Capacity

The effect of changing the arc fixed cost parameter is illustrated in Tables 3.52, 3.53 and 3.54 as well as in Figure 3.26 and 3.27. By reducing the arc capacities, the losgistics system become more constrained hence the overall system level cost increases, albeit slightly. This is a result of the over capacity in the baseline scenario (e.g., there is no cost decrease between the +10% and +20% scenario).There are three observations with this sensitivity analysis. First, the transportation cost increases with reduced arc transportation capacity. Second the fixed cost of selecting arcs increase as more and more arcs are being used. This is especially more apparent for the Plant-MC echelon than the MC-Ramp echelon. Third, the fixed cost per shipment increases as one way of using the arcs that are preferable (e.g. lower variable transportation cost and fixed costs) under more restrictive capacity is to increase the frequency of shipments.

Scenarios	Total Cost	TRPC	FCA	FCPS	FIHC	ITHC	Expediting	Lost Sales
Δu^0_{ij}=-20%	25,659,404	11,120,800	2,848,235	1,365,555	5,408,574	4,723,165	193,076	-
Baseline	24,672,205	10,861,388	2,346,015	1,057,115	5,579,396	4,555,997	272,294	-
Δu^0_{ij}=+20%	23,829,183	10,523,675	1,905,445	1,148,930	5,259,763	4,702,678	288,692	-

Table 3.52. Effect of changing Arc Capacities on Logistics Costs (All echelons).

	PLANT-MC				MC-RAMP				PLANT-PLANT			
Scenarios	**TRPC**	**ITHC**	**FCA**	**FCPS**	**TRPC**	**ITHC**	**FCA**	**FCPS**	**TRPC**	**ITHC**	**FCA**	**FCPS**
Δu^0_{ij}=-20%	6,958,317	789,282	923,400	437,725	4,046,475	3,897,325	1,835,835	872,295	116,009	789,282	89,000	55,535
Baseline	6,896,955	765,736	716,400	331,075	3,907,651	3,773,693	1,546,915	700,145	56,781	765,736	82,700	25,895
Δu^0_{ij}=+20%	6,730,712	767,057	570,500	517,300	3,700,876	3,904,216	1,272,120	598,070	92,087	767,057	62,825	33,560

Table 3.53. Effect of changing the Arc Capacities on Logistics Costs by echelon and facility.

	FIHC		
Scenarios	**PLANT**	**MC**	**RAMP**
Δu^0_{ij}=-20%	553,685	87,582	4,767,312
Baseline	256,757	368,892	4,953,753
Δu^0_{ij}=+20%	522,541	269,099	4,468,130

Table 3.54. Effect of changing Arc Capacities on Inventory Holding Cost by each facility

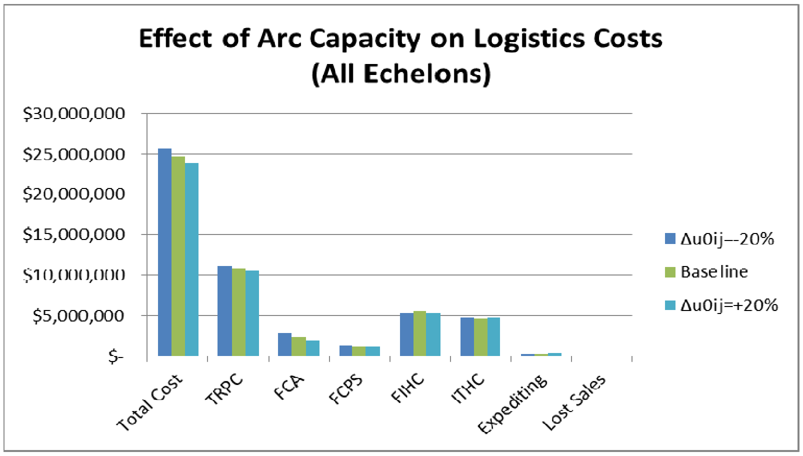
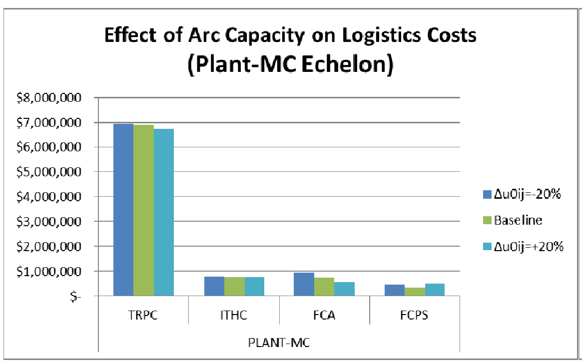
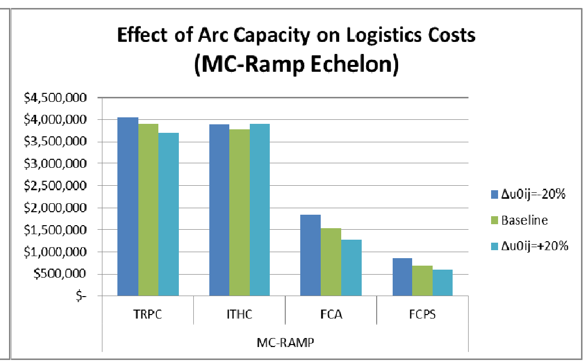


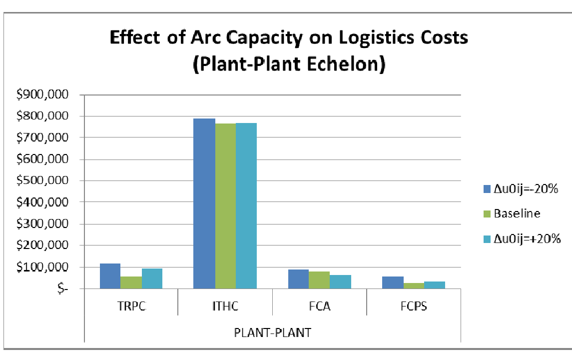
Figure 3.26. Effect of changing Arc Capacities on Logistics Costs.



(a)



(b)



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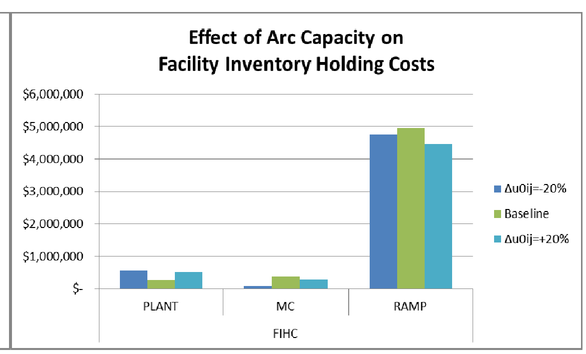

(d)

Figure 3.27. Effect of changing Arc Capacities on Logistics Costs by echelon and facility type.

3.8Cost Comparison: Baseline No Collaboration vs. Baseline Collaboration

In our experimental study (Table 3.55), we observed abouta 3% decrease in the total network cost when there is collaboration. We observed most significant cost decrease in FCPS (about 36%). This is because collaboration allows consolidation of shipments from plants to mixing centers as opposed to the no collaboration. The next decrease in cost parameter is the FCA (about 12%) due to the use of lesser arcs with collaboration vs. no collaboration. However, we observed that the transportation cost increases slightly for collaboration than non-collaboration. This is because there are more frequent deliveries with collaboration vs. non-collaboration. The other interesting observation is that the facilities in-house holding cost increases for collaboration for accumulation and consolidation. The expedited shipment cost is also reduced for collaboration. The Lost Sales are in-significant for both collaboration and non-collaboration.

Cost Parameters	Base Line No Collaboration	Base Line Collaboration	Cost Decrease		Cost Increase	
TC	$ 25,402,749	$ 24,672,205	$ 730,544	2.9%		
TRP	$ 10,686,480	$ 10,861,388			$ 174,908	1.6%
FCA	$ 2,660,735	$ 2,346,015	$ 314,720	11.8%		
FCPS	$ 1,647,580	$ 1,057,115	$ 590,465	35.8%		
FIHC	$ 5,320,570	$ 5,579,396			$ 258,826	4.9%
ITHC	$ 4,814,520	$ 4,555,997	$ 258,523	5.4%		
Expediting	$ 272,864	$ 272,294	$ 570	0.2%		
Lost Sales	$ -	$ -	$ -	-	$ -	-

Table 3.55. Collaboration vs. no Collaboration Cost Comparison Table

CHAPTER 4

CASE STUDIES

4.1 Introduction

We discussed why collaboration between US automakers is important in Chapter 1. In Chapter 2, we developed collaboration framework between competing companies in three operational, tactical, and strategic levels. We formulated and developed a multi-period multi-commodity MCNF mathematical model in Chapter 3.

In this chapter we describe the practical application of our proposed collaboration model in the US Automotive Industry. The network structure information related to this Case Study was provided by Ford and GM Outbound Logistics management. Our goal is to validate our collaboration framework and mathematical model through this case study.

In the consecutive sections of this chapter, we will test our multi-period, multi-product outbound logistics network optimization model with and without collaboration and compare the results to see if collaboration works for the US Automakers. We will use the following approach:

- First, we will run the model for Ford and GM respectively without collaboration. We will compare the network performance of Ford and GM.

- Second, we will use the model on operational and tactical level collaborationwithin the existing network structure of Ford and GM. In this collaboration, both Ford and GM will use each other's existing networks such as plants and mixing centers to assess the impact. We will then compare the performance of with and without collaboration.

4.2 US Outbound Logistics Rail Network (OLRN)

The US outbound logistics network is a complex network. Attributable to this network complexity, the scope of collaboration for outbound vehicle distribution in the automotive industry is enormous. For example, Ford Motor Company alone has dozens of Vehicle Assembly Plants, *Mixing Centers*, and hundreds of Ramps serving several thousand dealerships throughout the United States. The automotive OEM contracts the Truck haulers to transport finished vehicles directly from the Assembly Plants and the MixingCenters to the dealers. The automotive OEM contracts the Rail Carrier companies to transport finished vehicles from the Assembly Plants to the Ramps directly or via Mixing Centers. The consolidation and transshipment of finished vehicles at the Mixing Centers are usually managed and operated by the Rail Carrier companies such as Norfolk Southern manages vehicles for Ford Motor Company.

Scoping the research problem is critical for tractability and practicality of the models and methods. This research focuses on the distribution of finished vehicles from the Assembly Plants to the Ramps via Mixing Centers. In the following section, we will talk about Ford and GM rail network in the USA.

4.2.1 Ford Rail Network

The north American outbound logistics rail network of Ford Motor Company consist of twelve Assembly Plants, six Mixing Centers, and 59 Ramps (Figure 4.1). Ford has nine (9) vehicle Assembly Plants in the USA, one (1) in Canada, and two (2) in Mexico. The Ford vehcile assembly plants are: Auto Alliance International Assembly Plant (USA), Dearborn Truck Assembly Plant (USA), Chicago Assembly Plant (USA), Kansas City Assembly Plant (USA), Kentucky Truck Plant (USA), Louisville Assembly Plant (USA), Michigan Assembly Plant (USA), Ohio Assembly Plant (USA), Twin Cities Assembly Plant (USA), Oakville Assembly Plant (Canada), Cuatitlan Assembly Plant (Mexico), and Hermosillo Assembly Plant (Mexico). The Mixing Centers (also called Consolidation Centers) are Flatrock, Melvindale, Newbostown, Walbridge, Lordstown, and Malkahm. Some of the Rail Carrier companies of Ford outbound logistics are BN, CN, CP, CNC, CSX, FXE, KCS, NS, TFM, UP. The Ford vehicle make and model by planys are in Table 4.1.

Figure 4.1: Outbound Rail Logistics Network of Ford

The vehicle makes and model of Ford Motaor Company are:

1. Auto Alliance Int. (Flat Rock, Michigan) – Ford Mustang, Mazda 6
2. Dearborn Truck Assembly Plant (Dearborn, Michigan) – Ford F-150
3. Chicago Assembly Plant (Chicago, Illinois) – Taurus, Lincoln MKS
4. Kansas City Assembly Plant (Claycomo, Missouri) - Ford F-150, Ford Escape/Hybrid, Mazda Tribute
5. Kentucky Truck Plant (Louisville, Kentucky) - Ford Superduty, Ford Expedition, Lincoln Navigator
6. Louisville Assembly Plant (Louisville, Kentucky) - Ford Kuga, Ford Escape
7. Wayne Assembly Plant (Wayne, Michigan) - Ford Focus, Ford C-Max
8. Ohio Assembly Plant (Avon Lake, Ohio) – Econoline

9. Twin Cities Assembly Plant (Saint Paul, Minnesoeta) – Ford Ranger, Mazda B-Series
10. Oakville Assembly Plant (Oakville, Ontario, Canada) – Ford MKX, Ford Edge, Ford Flex, Lincoln MKT
11. Cuatitlan Assembly Plant (Cuautitln, Izcalli, Mexico) – Ford f-Series, Ford Fiesta, Ford Ikon
12. Hermosillo Assembly Plant (Hermosilo, Sonora, Mexico) – Ford Fusion, Lincoln MKZ

4.2.2 GM Rail Network

The General Motors (GM) has seventeen (17) Vehicle Assembly Plants, 4 Mixing Centers, and 57 destination Ramps in the North American Operations (Figure 4.2). GM has twelve (12) vehicle assembly plants in the USA, two 92) in Canada, and three (3) in Mexico. The GM Vehicle Assembly Plants are: Arlington Assembly Plant (USA), Hamtramck Assembly Plant (USA), Flint Truck Assembly plant (USA), Charlotte Assembly Plant (USA), Lansing Grand River Assembly Plant (USA), Orion Assembly Plant (USA), Wentzville Assembly Plant (USA), Fort Wayne assembly Plant (USA), Fairfax Assembly Plant (USA), Shreveport Assembly Plant (USA), Lordstown Assembly Plant (USA), Bowling Green Assembly Plant (USA), Ingersoll Assembly Plant (Canada), Oshawa Assembly Plant (Canada), Ramos Assembly Plant (Mexico), San Louis Potosi Assembly Plant (Mexico), Silao Assembly Plant (Mexico). The four Mixing

Centers are located in Melvindale and New Boston of Michigan, Toledo-Ohio, and Windsor-Canada. The major Rail carrier companies of GM are CN, CPRS, CSXT, FXE, KCSM, KCSR, NS, and UP. The GM vehicle make and model by planys are in Table 4.1.

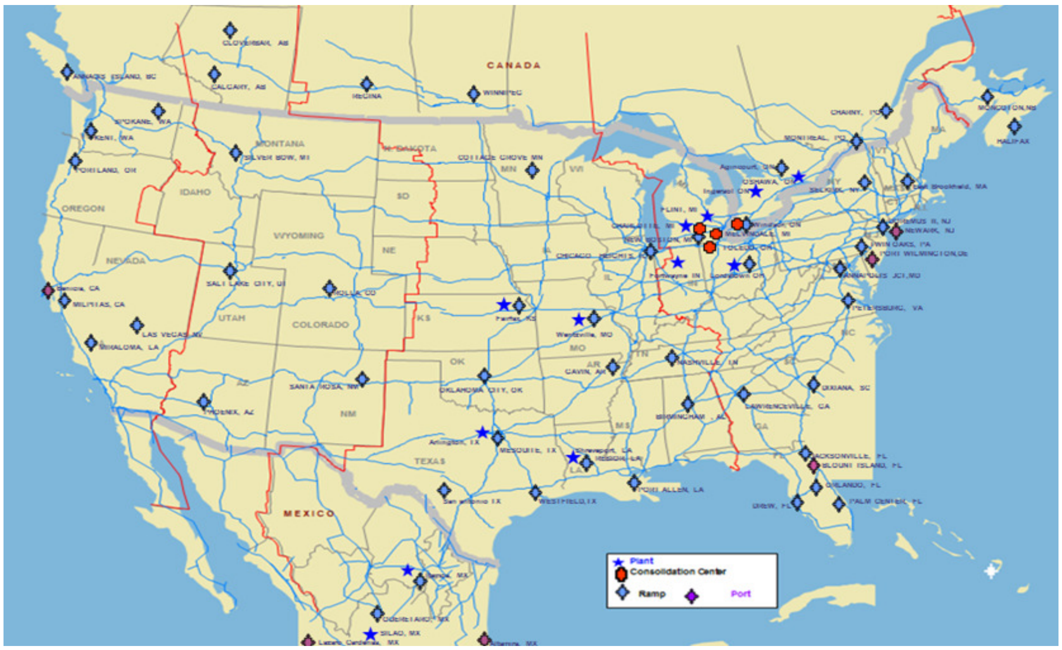

Figure 4.2: Outbound Rail Logistics Network of GM

The vehicle makes and model of General Motors are:

1. Hamtramck Assembly Plant (Hamtramck, Michigan) – Volts, Lucerne
2. Flint Truck Assembly (Flint, Michigan) - Chevy Silverado, GMAC Sierra
3. Charlotte Assembly Plant (Lansing Delta Township, Michigan) - Chevrolet Traversa, GMC Acadia, Buick Enclave
4. Lansing Grand River Assembly Plant (Lansing, Michigan) – CTS, STS
5. Orion Assembly Plant (Orion, Michigan) - Chevrolet Sonic, Buick Verano

6. Wentzville Assembly Plant (Wentzville, Missouri) - Chevrolet Express, GMAC Savana
7. Fort Wayne Assembly Plant (Roanoke, Indiana) - Chevrolet Silverado, GMC Sierra
8. Fairfax Assembly Plant (Fairfax, Kansas) - Chevrolet Malibu, Buick Lacrosse
9. Shreveport Assembly Plant (Shreveport, Louisiana) - Chevrolet Colorado, GMCCanyon
10. Lordstown Assembly Plant (Lords Town, Ohio) - Chevrolet Cruze
11. Bowling Green Assembly Plant (Bowling Green, Kentucky) – Corvette
12. Arlington Assembly Plant (Arlington, Texas) - Cadillac Escalade, Chevrolet Suburban, Chevrolet Tahoe, GMAC Yukon
13. Ingersoll Assembly Plant (Ingersoll, Ontario, Canada) - Chevrolet Equinox, GMC Terrain
14. Oshawa Assembly Plant (Oshawa, Ontario, Canada) - Chevrolet Impala, Chevrolet Camaro, GMC Equinox
15. Ramos Assembly Plant (Ramos Arizpe, Mexico) - Chevrolet C2, Chevrolet HHR, Cadillac SRX
16. San Louis Potosi Assembly Plant (San Louis Potosi, Mexico) - Chevrolet Aveo, Pontiac G3
17. Silao Assembly Plant (Silao, Mexico) - Cadillac Escalade, Chevrolet Suburban, GMC Yukon, Chevrolet Avalanche

4.3 Case Study Networks

To test and validate our mathematical model, we chose three different US Automakers representative netowrks. Our goal is to test any impacts on increasing the network size.

The 1st network consist of (2) Assembly Plants, two (2) Mixing Centers, and two (2) Ramps from Ford Motor Company and two (2) Assembly Plants, two (2) Mixing Centers, and two (2) Ramps from General Motors. Therefore, the Ford representative network consists of seven (6) nodes and GM six (6) nodes in this case study. There are total fifteen (12) nodes when Ford and GM collaborate with each other (Table 4.1a).

The 2nd network consist of (2) Assembly Plants, two (2) Mixing Centers, and three (3) Ramps from Ford Motor Company and two (2) Assembly Plants, two (2) Mixing Centers, and four (4) Ramps from General Motors. Therefore, the Ford representative network consists of seven (7) nodes and GM eight (8) nodes in this case study. There are total fifteen (15) nodes when Ford and GM collaborate with each other (Table 4.1b).

The 3rd network consist of (2) Assembly Plants, two (2) Mixing Centers, and six (6) Ramps from Ford Motor Company and two (2) Assembly Plants, two (2) Mixing Centers, and six (6) Ramps from General Motors. Therefore, the Ford representative network consist of total ten (10) nodes and GM ten (10) nodes in this Case study.There are total twenty (20) nodes when Ford and GM collaborates with each other (Table 4.1c).

Company	Assembly Plants	Mixing Centers	Ramp
Ford	Auto Alliance, MI Wayne Assembly Plant, MI	New Boston, MI Markham, IL	Dixiana (SC) Jacksonville (FL)
GM	Charolett Assembly Plant, MI Orion Assembly Plant, MI	Toldeo, OH Chicago, IL	Dixiana (SC) Jacksonville (FL)

Table 4.1a: Representative Network1

Company	Assembly Plants	Mixing Centers	Ramp
Ford	Auto Alliance, MI Wayne Assembly Plant, MI	New Boston, MI Markham, IL	Dixiana (SC) Jacksonville (FL) Twin Oaks (PA)
GM	Charolett Assembly Plant, MI Orion Assembly Plant, MI	Toldeo, OH Chicago, IL	Dixiana (SC) Jacksonville (FL) Twin Oaks (PA) Palm City (FL)

Table 4.1b: Representative Network2

Company	Assembly Plants	Mixing Centers	Ramp
Ford	Auto Alliance, MI Wayne Assembly Plant, MI	New Boston, MI Markham, IL	Dixiana (SC) Jacksonville (FL) Twin Oaks (PA) Palm City (FL) Rolla (CO) Salt Lake (UT)
GM	Charolett Assembly Plant, MI Orion Assembly Plant, MI	Toldeo, OH Chicago, IL	Dixiana (SC) Jacksonville (FL) Twin Oaks (PA) Palm City (FL) Rolla (CO) Salt Lake (UT)

Table 4.1c: Representative Network3

4.4 US Outbound Logistics data

We used Fords 2010 production data to analyze the performance of Ford networks in this Case study. We generated representative data for GM production using 2010 market share in comparison to the Ford data. Due to the sensitivity of the cost data, we generated representative cost data after discussing with the Ford and GM management. We used \$.50 per vehicle per mile transportation cost for the Ford vehicles and \$.55 per vehicle per mile for the GM vehicles. The average inventory holding penalty cost is assumed to be \$3.5 per vehicle per day for the Ford Motor Company vehicles and \$3.75 per vehicle per mile for the GM vehicles. All other cost such as fixed arc cost and fixed cost per shipments are based on the best average information provided by the Ford and GM Outbound Logistics personnel during phone and personal interviews.

4.5 Computational Results:

We use the GM and Fords representative network data and ran multi-commodity, multi-period MCNF model for this Case study. We used ILOG commercial package in solving this problem. First we ran GM and Ford networks without collaboration followed by collaboration. The results are displayed in Table 4.2.

We compare the results between GM and Ford performing independently and collaboratively. We find that collaboration between Ford and GM does save cost. However, in some cost parameters such as Fixed Cost per shipment, In-transit Inventory cost, facility inventory holding cost etc. increases with collaboration which is counter intuitive.

Several interesting observations can be made. First increasing the network size for collaboration increases the cost savings. However as we see in the case of Network 3, these savings depend on the demand allocation across ramps, In other words, the size as well as the demand characteristics of the expanded network determine the total cost savings.

Ford (2P, 2M, 2R), GM (2P, 2M, 2R)

Cost	No Collaboration			With Collaboration			Cost
	GM	Ford	GM+Ford	GM	Ford	GM+Ford	Savings
Transportation_Cost	$ 1,333,766	$ 900,926	$ 2,234,692	$ 1,018,714	$ 693,567	$ 1,712,281	23%
Fixed_Cost_Arc	$ 208,500	$ 240,000	$ 448,500	$ 407,500		$ 407,500	9%
Fixed_Cost_PerShipment	$ 125,650	$ 59,050	$ 184,700	$ 212,350		$ 212,350	Increased
Inventory_Holding_Cost	$ 402,937	$ 308,838	$ 711,775	$ 378,499	$ 327,560	$ 706,059	1%
In_Transit_Inventory_Cost	$ 9,553	$ 6,562	$ 16,115	$ 8,825	$ 10,049	$ 18,874	Increased
Expedited Shipment Cost	$ -	$ -	$ -	0		$ -	
Lost Sales	$ 14,525.00	750	$ 15,275	7500		$ 7,500	51%
Total Cost	$ 2,094,931	$ 1,516,126	$ 3,611,057			$ 3,064,564	15%

Ford (2P, 2M, 3R), GM (2P, 2M, 4R)

Cost	No Collaboration			With Collaboration			Cost
	GM	Ford	GM+Ford	GM	Ford	GM+Ford	Savings
Transportation_Cost	$ 4,609,929	$ 2,136,289	$ 6,746,218	$ 3,226,543	$ 1,535,157	$ 4,761,700	29%
Fixed_Cost_Arc	$ 541,900	$ 370,000	$ 911,900	$ 829,400		$ 829,400	9%
Fixed_Cost_PerShipment	$ 694,900	$ 121,790	$ 816,690	$ 722,700		$ 722,700	12%
Inventory_Holding_Cost	$ 355,896	$ 296,122	$ 652,018	$ 342,212	$ 313,403	$ 655,615	Increased
In_Transit_Inventory_Cost	$ 32,792	$ 15,344	$ 48,136	$ 28,244	$ 24,168	$ 52,412	Increased
Expedited Shipment Cost	$ 1,420.78	$ -	$ 1,421	5200		$ 5,200	Increased
Lost Sales	$ -	$ -	$ -	276250		$ 276,250	Increased
Total Cost	$ 6,236,838	$ 2,939,545	$ 9,176,382			$ 7,303,277	20%

Ford (2P, 2M, 6R), GM (2P, 2M, 5R)

Cost	No Collaboration			With Collaboration			Cost
	GM	Ford	GM+Ford	GM	Ford	GM+Ford	Savings
Transportation_Cost	$ 5,961,469	$ 4,053,051	$ 10,014,519	$ 4,266,866	$ 3,453,848	$ 7,720,714	23%
Fixed_Cost_Arc	$ 588,650	$ 605,000	$ 1,193,650	$ 1,313,260		$ 1,313,260	-10%
Fixed_Cost_PerShipment	$ 526,750	$ 225,335	$ 752,085	$ 823,380		$ 823,380	Increased
Inventory_Holding_Cost	$ 387,551	$ 278,676	$ 666,227	$ 347,458	$ 292,359	$ 639,817	4%
In_Transit_Inventory_Cost	$ 42,433	$ 29,475	$ 71,908	$ 44,925	$ 35,834	$ 80,759	Increased
Expedited Shipment Cost	$ 2,114	300	$ 2,414	11550		$ 11,550	Increased
Lost Sales	$ 100,000	29000	$ 129,000	467500		$ 467,500	Increased
Total Cost	$ 7,608,967	$ 5,220,837	$ 12,829,804			$ 11,056,981	14%

Table 4.2 Collaboration vs no-Collaboration

Another observation is the effect of collaboration on different cost elements. Analyzing all three networks, we observe that collaboration always benefits the transportation cost due to the increased availability of alternative (and lesser cost) transportation paths. In contrast, while some networks experience reduction in the fixed costs, others experience increase in the fixed cost. This is due to the fact that the savings in the transportation costs dominates the slight increase in the fixed costs.

In Figure 4.3 we observe that as the size of the network increases (number of nodes), the total logistics cost increases for both collaboration and non-collaboration scenarios. However, the increase is higher for the non-collaboration case.

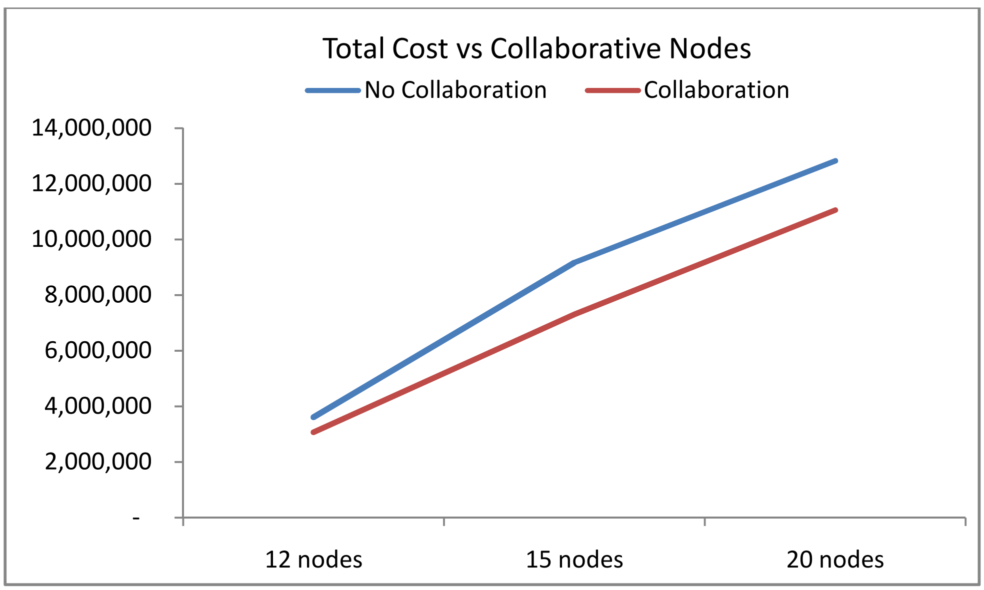

Figure 4.3. Collaboration vs no-Collaboration

Similarly, In Figure 4.4 we observe that, as the size of the network increases (number of nodes), the transportation cost increases for both collaboration and non-collaboration. However, the increase is higher for the non-collaboration case.

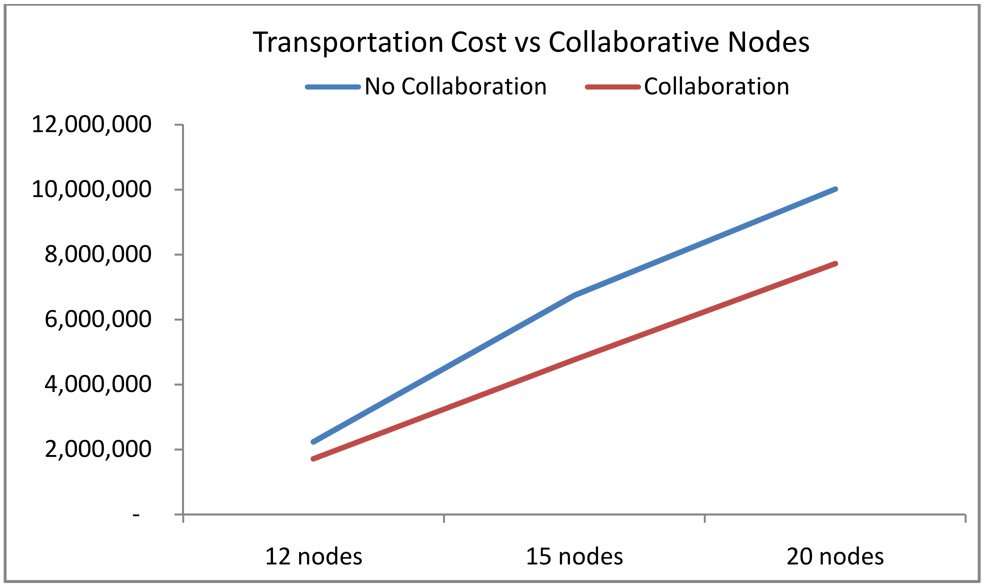

Figure 4.4 Collaboration vs no-Collaboration

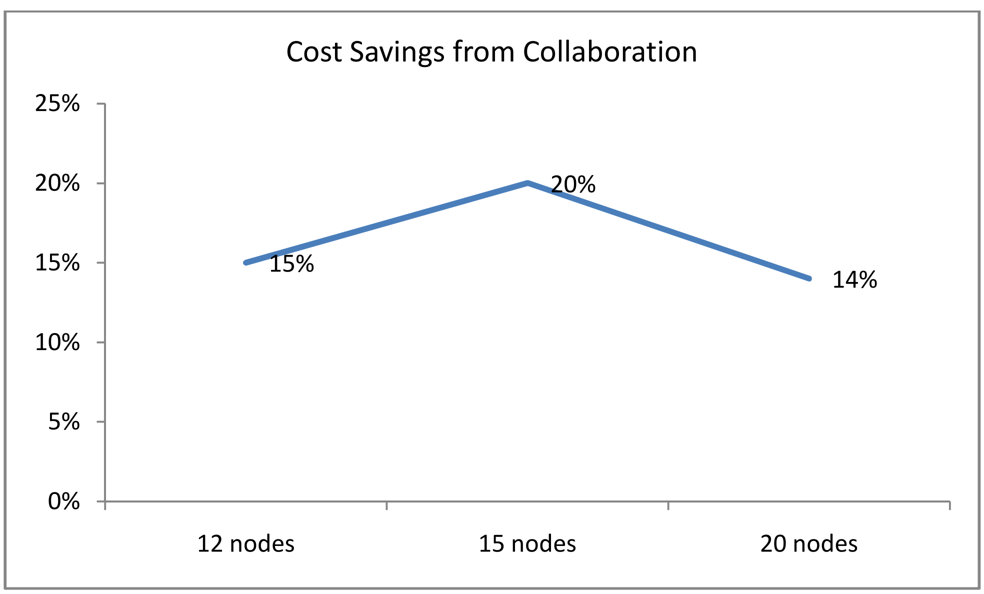

Figure 4.5Cost savings between Collaboration vs no-Collaboration

In Figure 4.5 we observe that as the size of the network increases so is the percent cost savings upto a limit and then the cost saving diminishes. This indicates that while considering the collaboration, it is important to identify the parts of the network where the potential benefits are highest so as to justify the additional cost necessary for establishing collaboration.

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 Summary

We developed a multi-period and multi-product MCNF model for the outbound logistics network for the US Automakers. Then we developed three different levels of collaboration model: operational, tactical, and strategic. We show that the US Automakers have ample of opportunities to gain economies of scales from collaborative outbound logistics network and thus reduce cost and increase profit margin.

5.2 Novelty and Research Contributions

We have two major contributions to the outbound logistics literature: i) the introduction of a framework for intra- and inter-OEM collaboration, ii) the development of novel logistics network design and flow models integrated with frequency based inventory modeling and lost sales and expedited shipping due to shortage. Besides the contribution to the academic literature, the proposed collaborative distribution system is a new concept in the automotive industry. Hence, this novel research work will also benefit to the practitioners. The novelty and contribution of this research are therefore:

- Developing an integrated framework for intra- and inter-OEM collaboration for the automotive industry by combining concepts such as consolidation, transshipments, 3PL and hub and facility location etc.
- Developing new logistics network models by integrating the classical MCNF model with efficient inventory models and lost sales and expediting models. The novelty of our work is that the application of ship frequency based inventory models in the outbound logistics which is new to the researchers and the practitioners. Further, the integration of the effect of network flow decisions on the costs of expediting and lost sales is novel. We also show that these models could be linearized to be able to solve efficiently.

5.3 Limitations and Scope for Further Research

Although this research has presented a practical approach to build a collaboration framework between rival automotive companies, there are opportunities to extend this work. The limitations or the scope for future research can be grouped into the following categories as follows:

- This Collaborative framework can be extended to the automotive dealer network and the concept of Lost sales and Expedited Shipments can be measured using stochastic analysis.
- Queuing theory can be applied to the outbound collaborative framework to measure wait time and service rate.

APPENIXA: ILOG MODEL OF MCNF BASE MODEL

A-1: Model File

```
// PARAMETERS
//----------------
// Set Constants
intBigM = ... ;

// NO of NODES
intNbAllnodes = ...;
intNbPlants=...;
intNbMixingCenters=...;
intNbRamps=...;

// SETS OF NODES
// first nodes are plants (PlantNodes); second are mixing center (MCNodes); next
is Ramp Nodes (RampNodes )
rangeAllnodes = 1..NbAllnodes;
rangePlantNodes = 1..NbPlants;
rangeMCNodes = NbPlants+1..NbPlants+NbMixingCenters;
rangeRampNodes = NbAllnodes-NbRamps+1..NbAllnodes;

// Union sets (PlantMCNodes and MCRampNodes )
range PlantMCNodes = 1..NbPlants+NbMixingCenters;
range MCRampNodes = NbPlants+1..NbAllnodes;

// linearization index
int K=5;

// number of periods and set of time periods
intNbPeriod = ...;
range Period = 1..NbPeriod;
// No of time units in a period
int L=...;

//float c[PlantMCNodes][MCRampNodes] = ...;  // transportation cost
//float u[PlantMCNodes][MCRampNodes] = ...;  // arc capacity
//float f[PlantMCNodes][MCRampNodes] = ...;  // fixed cost of choosing an arc
//float h[PlantMCNodes][MCRampNodes] = ...;  // fixed cost per shipment
//float tov[PlantMCNodes][MCRampNodes] = ...; // transportation lead time on arc

float c[Allnodes][Allnodes] = ...;  // transportation cost
float u[Allnodes][Allnodes] = ...;  // arc capacity
```

```
float f[Allnodes][Allnodes] = ...;  // fixed cost of choosing an arc
float h[Allnodes][Allnodes] = ...;  // fixed cost per shipment
float tov[Allnodes][Allnodes] = ...; // transportation lead time on arc

float s[Allnodes][Period] = ...;  // supply/demand amount at each node
float I_zero[Allnodes] = ...;  // initial inventory at the beginning of time period

float p = ...; // inventory holding cost per vehicle per time period

// Decision variables
dvar  float+  X[PlantMCNodes][MCRampNodes][Period] ; // shipment size on
each arc and period
dvar  float+  X_PERIOD_1[Allnodes][Allnodes];
dvar  float+  X_PERIOD_2[Allnodes][Allnodes];
dvar  float+  X_PERIOD_3[Allnodes][Allnodes];

dvarint+  R[Allnodes][Allnodes][Period] ; // shipment frequency on each
arc in each period
dvarint+  R_PERIOD_1[Allnodes][Allnodes];
dvarint+  R_PERIOD_2[Allnodes][Allnodes];
dvarint+  R_PERIOD_3[Allnodes][Allnodes];

dvarboolean  Y[PlantMCNodes][MCRampNodes][Period]; //binary decision for
using arc
dvarboolean  Y_PERIOD_1[Allnodes][Allnodes];
dvarboolean  Y_PERIOD_2[Allnodes][Allnodes];
dvarboolean  Y_PERIOD_3[Allnodes][Allnodes];

dvarboolean  Z[1..K][PlantMCNodes][MCRampNodes][Period] ;
//r_ijt=sum(k=1...K)2^(k-1).z_kijt

dvar float  Q[Allnodes][Period] ;  //inventory deposit (>0) withdraw (<0) at each
node and time period
dvar float+    I[Allnodes][Period] ;  //inventory at the beginning of each period

dvar float+  W[1..K][PlantMCNodes][MCRampNodes][Period] ; // reformulation
variable w_kijt=x_ijt.z_kijt


dvar float+  Transportation_Cost;
dvar float+  Transportation_Cost_P_M;
dvar float+  Transportation_Cost_M_R;
dvar float+  Transportation_Cost_M_M;
dvar float+  Transportation_Cost_P_R;
```

```
dvar float+  Fixed_Cost_ARC;
dvar float+  Fixed_Cost_ARC_P_M;
dvar float+  Fixed_Cost_ARC_M_R;
dvar float+  Fixed_Cost_ARC_M_M;
dvar float+  Fixed_Cost_ARC_P_R;

dvar float+  Fixed_Cost_PerShipment;
dvar float+  Fixed_Cost_PerShipment_P_M;
dvar float+  Fixed_Cost_PerShipment_M_R;
dvar float+  Fixed_Cost_PerShipment_M_M;
dvar float+  Fixed_Cost_PerShipment_P_R;

dvar float+  Inventory_Holding_Cost;
dvar float+  Inventory_Holding_Cost_Plant;
dvar float+  Inventory_Holding_Cost_MC;
dvar float+  Inventory_Holding_Cost_Ramp;

dvar float+  In_Transit_Inventory_Cost;
dvar float+  In_Transit_Inventory_Cost_P_M;
dvar float+  In_Transit_Inventory_Cost_M_R;
dvar float+  In_Transit_Inventory_Cost_M_M;
dvar float+  In_Transit_Inventory_Cost_P_R;

dvar float  Inventory_Holding_Cost_Plant_perPeriod[Period];
dvar float  Inventory_Holding_Cost_MC_perPeriod [Period];
dvar float  Inventory_Holding_Cost_Ramp_perPeriod [Period];

minimize

Transportation_Cost + Fixed_Cost_ARC + Fixed_Cost_PerShipment +
Inventory_Holding_Cost_Plant+
                            Inventory_Holding_Cost_MC
+Inventory_Holding_Cost_Ramp + In_Transit_Inventory_Cost ;


//  CONSTRAINTS //

subject to {

// LEVELS X
forall(i in PlantMCNodes, j in MCRampNodes)  X_PERIOD_1[i][j]==X[i][j][1];
forall(i in PlantMCNodes, j in MCRampNodes)  X_PERIOD_2[i][j]==X[i][j][2];
forall(i in PlantMCNodes, j in MCRampNodes)  X_PERIOD_3[i][j]==X[i][j][3];
// LEVELS R
```

```
forall(i in PlantMCNodes, j in MCRampNodes)  R_PERIOD_1[i][j]==R[i][j][1];
forall(i in PlantMCNodes, j in MCRampNodes)  R_PERIOD_2[i][j]==R[i][j][2];
forall(i in PlantMCNodes, j in MCRampNodes)  R_PERIOD_3[i][j]==R[i][j][3];


// LEVELS Y
forall(i in PlantMCNodes, j in MCRampNodes)  Y_PERIOD_1[i][j]==Y[i][j][1];
forall(i in PlantMCNodes, j in MCRampNodes)  Y_PERIOD_2[i][j]==Y[i][j][2];
forall(i in PlantMCNodes, j in MCRampNodes)  Y_PERIOD_3[i][j]==Y[i][j][3];

// FLOW CONSERVATION CONSTRAINTs
//--------------------------------
// Mixing Center flow conservation
forall(i in MCNodes, t in Period)
ct_FLOW_BALANCE_MC:
	Q[i][t] + sum(j in MCRampNodes, k in 1..K: i!=j) pow(2,k-1) * W[k][i][j][t]
		- sum(j in PlantMCNodes, k in 1..K: i!=j) pow(2,k-1) * W[k][j][i][t] == 0 ;

// Plant flow conservation
forall(i in PlantNodes, t in Period)
ct_FLOW_BALANCE_PLANT:
	Q[i][t] + sum(j in MCRampNodes, k in 1..K) pow(2,k-1) * W[k][i][j][t]

				== s[i][t] ;

// Ramp flow conservation
forall(i in RampNodes, t in Period)
ct_FLOW_BALANCE_RAMP:
	Q[i][t]
		- sum(j in PlantMCNodes, k in 1..K) pow(2,k-1) * W[k][j][i][t] == s[i][t] ;

// PLANT PRODUCTION AND RAMP DEMAND CONSERVATION
CONSTRAINTs
//--------------------------------

// NON-NEGATIVE INVENTORY AT THE BEGINNING OF EACH PERIOD
//-------------------------------------
// Nonnegative MC inventory at the beginning of each period
	forall(i in MCNodes, t in Period)
	I[i][t] + sum(j in PlantMCNodes, k in 1..K: i!=j) pow(2,k-1) * W[k][j][i][t] >=
			sum(j in MCRampNodes, k in 1..K: i!=j) pow(2,k-1) *
W[k][i][j][t];

// Nonnegative PLANT inventory at the beginning of each period
```

```
        forall(i in PlantNodes, t in Period)
        I[i][t] + s[i][t] >=
                        sum(j in MCRampNodes, k in 1..K) pow(2,k-1) * W[k][i][j][t];

// Nonnegative RAMP inventory at the beginning of each period
        forall(i in RampNodes, t in Period)
        I[i][t] + sum(j in PlantMCNodes, k in 1..K) pow(2,k-1) * W[k][j][i][t] >=
                        -s[i][t];

// NON-NEGATIVE AVERAGE INVENTORY CONDITION AT EACH PERIOD
//------------------------------------
// Nonnegative AVERAGE MC inventory at each period
        forall(i in MCNodes, t in Period)
        I[i][t] + sum(j in PlantMCNodes: i!=j) X[j][i][t] >=
                        sum(j in MCRampNodes: i!=j) X[i][j][t];

// Nonnegative AVERAGE PLANT inventory at each period
        forall(i in PlantNodes, t in Period)
        I[i][t] + s[i][t]/L >=
                        sum(j in MCRampNodes) X[i][j][t];

// Nonnegative AVERAGE RAMP inventory at each period
        forall(i in RampNodes, t in Period)
        I[i][t] + sum(j in PlantMCNodes) X[j][i][t] >=
                        -s[i][t]/L;


// ARC CAPACITY CONSTRAINT
//--------------------------
// Arc capacity constraint
forall(i in PlantMCNodes, j in MCRampNodes, t in Period: i!=j)
ct_ARC_CAPACITY:
       X[i][j][t] <= u[i][j] ;

// NO FLOW IF ARC NOT SELECTED
//----------------------------------
forall(i in PlantMCNodes, j in MCRampNodes, t in Period: i!=j)
ct02:
       X[i][j][t] <= BigM*Y[i][j][t] ;

// NO NEED TO SELECT ARC IF NOT SHIPPING
//----------------------------------
forall(i in PlantMCNodes,j in MCRampNodes, t in Period: i!=j )
ct03:
```

```
      Y[i][j][t] <= R[i][j][t] ;

// INVENTORY CONSERVATION
//-------------------------------------
forall(i in Allnodes)
     ct04:
      sum( t in Period ) Q[i][t] == 0 ;

forall(i in Allnodes, t in Period: t!=NbPeriod)
      ct05:
      I[i][1] + sum(tt in 1..t) Q[i][tt] >= 0 ;

forall(i in Allnodes)
      ct06:
      I[i][1] == I_zero[i];


// SHIP/PRODUCTION/DEMAND FREQUENCY FORMULAE
//---------------------------------------------
// Production frequency
// Fixed frequency


// Demand frequency
// Fixed frequency

// Ship frequency
forall(i in PlantMCNodes,j in MCRampNodes, t in Period: i!=j )
ct_Ship_Freq_MC:
       R[i][j][t] == sum(k in 1..K)  pow(2,k-1) * Z[k][i][j][t] ;

// Ship frequency cannot exceed no periods
        forall(i in PlantMCNodes,j in MCRampNodes, t in Period: i!=j )
       R[i][j][t] <= L;

// W X Z relation
//---------------------------------------------
// Mixing Center
forall(i in PlantMCNodes,j in MCRampNodes, t in Period, k in 1..K : i!=j )
     ct_WXZ_MC_1:
       W[k][i][j][t] >= X[i][j][t] - BigM*(1-Z[k][i][j][t]) ;
forall(i in PlantMCNodes,j in MCRampNodes, t in Period, k in 1..K : i!=j )
     ct_WXZ_MC_2:
       W[k][i][j][t] <= X[i][j][t] + BigM*(1-Z[k][i][j][t]) ;
```

```
forall(i in PlantMCNodes,j in MCRampNodes, t in Period, k in 1..K: i!=j )
     ct_WXZ_MC_3:
       W[k][i][j][t] <= BigM*Z[k][i][j][t] ;

// Plant
// Ramp


// COST Functions
//------------------------------
// TRANSPORTATION COST
Transportation_Cost>=
 sum(i in PlantMCNodes,j in MCRampNodes, t in Period, k in 1..K: i!=j )
      c[i][j] * pow(2,k-1) * W[k][i][j][t]  ;

Transportation_Cost_P_M ==
 sum(i in PlantNodes,j in MCNodes, t in Period, k in 1..K: i!=j )
      c[i][j] * pow(2,k-1) * W[k][i][j][t]  ;

Transportation_Cost_M_R ==
 sum(i in MCNodes,j in RampNodes, t in Period, k in 1..K: i!=j )
      c[i][j] * pow(2,k-1) * W[k][i][j][t]  ;

Transportation_Cost_M_M ==
 sum(i in MCNodes,j in MCNodes, t in Period, k in 1..K: i!=j )
      c[i][j] * pow(2,k-1) * W[k][i][j][t]  ;

Transportation_Cost_P_R ==
 sum(i in PlantNodes,j in RampNodes, t in Period, k in 1..K: i!=j )
      c[i][j] * pow(2,k-1) * W[k][i][j][t]  ;

// FIXED ARC COST
Fixed_Cost_ARC>=
   sum(i in PlantMCNodes,j in MCRampNodes, t in Period: i!=j )
        f[i][j]*Y[i][j][t] ;

Fixed_Cost_ARC_P_M  ==
   sum(i in PlantNodes,j in MCNodes, t in Period: i!=j )
        f[i][j]*Y[i][j][t] ;

Fixed_Cost_ARC_M_R  ==
   sum(i in MCNodes,j in RampNodes, t in Period: i!=j )
        f[i][j]*Y[i][j][t] ;
```

```
Fixed_Cost_ARC_M_M  ==
   sum(i in MCNodes,j in MCNodes, t in Period: i!=j )
        f[i][j]*Y[i][j][t] ;

Fixed_Cost_ARC_P_R  ==
   sum(i in PlantNodes,j in RampNodes, t in Period: i!=j )
        f[i][j]*Y[i][j][t] ;

// FIXED COST PER SHIPMENT
Fixed_Cost_PerShipment>=
 sum(i in PlantMCNodes,j in MCRampNodes, t in Period: i!=j )
           h[i][j]*R[i][j][t] ;

Fixed_Cost_PerShipment_P_M  ==
 sum(i in PlantNodes,j in MCNodes, t in Period: i!=j )
           h[i][j]*R[i][j][t] ;

Fixed_Cost_PerShipment_M_R  ==
 sum(i in MCNodes,j in RampNodes, t in Period: i!=j )
           h[i][j]*R[i][j][t] ;

Fixed_Cost_PerShipment_M_M  ==
 sum(i in MCNodes,j in MCNodes, t in Period: i!=j )
           h[i][j]*R[i][j][t] ;

Fixed_Cost_PerShipment_P_R  ==
 sum(i in PlantNodes,j in RampNodes, t in Period: i!=j )
           h[i][j]*R[i][j][t] ;

// INVENTORY HOLDING COST

Inventory_Holding_Cost>=Inventory_Holding_Cost_Plant+Inventory_Holding_Co
st_MC+Inventory_Holding_Cost_Ramp;

Inventory_Holding_Cost_Plant>=
   p*L*(
      sum(i in PlantNodes, t in Period) I[i][t]
      + sum(i in PlantNodes, t in Period) 0.5*s[i][t]/L*(L+1)
      - sum(i in PlantNodes, j in MCRampNodes, t in Period,k in 1..K) 0.5 *
pow(2,k-1)*W[k][i][j][t]
      - sum(i in PlantNodes, j in MCRampNodes, t in Period) 0.5 * X[i][j][t]
    );
Inventory_Holding_Cost_MC>=
   p*L*(
```

```
      sum(i in MCNodes, t in Period) I[i][t]
      + sum(i in MCNodes, j in PlantMCNodes, t in Period,k in 1..K: j!=i) 0.5 *
pow(2,k-1)*W[k][j][i][t]
      + sum(i in MCNodes, j in PlantMCNodes, t in Period: j!=i) 0.5 * X[j][i][t]
      - sum(i in MCNodes, j in MCRampNodes, t in Period,k in 1..K: j!=i) 0.5 *
pow(2,k-1)*W[k][i][j][t]
      - sum(i in MCNodes, j in MCRampNodes, t in Period: j!=i) 0.5 * X[i][j][t]
    );

Inventory_Holding_Cost_Ramp>=
    p*L*(
      sum(i in RampNodes, t in Period) I[i][t]
      + sum(i in RampNodes, j in PlantMCNodes, t in Period,k in 1..K) 0.5 *
pow(2,k-1)*W[k][j][i][t]
      + sum(i in RampNodes, j in PlantMCNodes, t in Period) 0.5 * X[j][i][t]
      - sum(i in RampNodes, t in Period) 0.5*-1*s[i][t]/L*(L+1)
    );

// INTRANSIT INVENTORY COST
In_Transit_Inventory_Cost>=
    p*(
      sum(i in PlantMCNodes,j in MCRampNodes, t in Period, k in 1..K: i!=j  )
pow(2,k-1) * W[k][i][j][t] * tov[i][j]
    );


In_Transit_Inventory_Cost_P_M ==
    p*(
      sum(i in PlantNodes,j in MCNodes, t in Period, k in 1..K: i!=j  )   pow(2,k-1) *
W[k][i][j][t] * tov[i][j]
    );

In_Transit_Inventory_Cost_M_R ==
    p*(
      sum(i in MCNodes,j in RampNodes, t in Period, k in 1..K: i!=j  )   pow(2,k-1) *
W[k][i][j][t] * tov[i][j]
    );

In_Transit_Inventory_Cost_M_M ==
    p*(
      sum(i in MCNodes,j in MCNodes, t in Period, k in 1..K: i!=j  )   pow(2,k-1) *
W[k][i][j][t] * tov[i][j]
    );
```

```
In_Transit_Inventory_Cost_P_R ==
    p*(
      sum(i in PlantNodes,j in RampNodes, t in Period, k in 1..K: i!=j  )   pow(2,k-1)
* W[k][i][j][t] * tov[i][j]
    );

//-----------THIS WAS TO CHECK FOR THE NONNEGATIVITY OF AVE
INVENTORY IN EACH PERIOD

forall(t in Period)
Inventory_Holding_Cost_Plant_perPeriod [t] ==
   p*L*(
      sum(i in PlantNodes) I[i][t]
      + sum(i in PlantNodes ) 0.5*s[i][t]/L*(L+1)
      - sum(i in PlantNodes, j in MCRampNodes, k in 1..K) 0.5 * pow(2,k-
1)*W[k][i][j][t]
      - sum(i in PlantNodes, j in MCRampNodes) 0.5 * X[i][j][t]
    );

forall(t in Period)
Inventory_Holding_Cost_MC_perPeriod [t] ==
   p*L*(
      sum(i in MCNodes) I[i][t]
      + sum(i in MCNodes, j in PlantMCNodes,k in 1..K: j!=i) 0.5 * pow(2,k-
1)*W[k][j][i][t]
      + sum(i in MCNodes, j in PlantMCNodes: j!=i) 0.5 * X[j][i][t]
      - sum(i in MCNodes, j in MCRampNodes,k in 1..K: j!=i) 0.5 * pow(2,k-
1)*W[k][i][j][t]
      - sum(i in MCNodes, j in MCRampNodes: j!=i) 0.5 * X[i][j][t]
    );

forall(t in Period)
Inventory_Holding_Cost_Ramp_perPeriod [t] ==
    p*L*(
      sum(i in RampNodes) I[i][t]
      + sum(i in RampNodes, j in PlantMCNodes,k in 1..K) 0.5 * pow(2,k-
1)*W[k][j][i][t]
      + sum(i in RampNodes, j in PlantMCNodes) 0.5 * X[j][i][t]
      - sum(i in RampNodes) 0.5*-1*s[i][t]/L*(L+1)
    );

//-----------
}
```

A-2: Data File

```
// Input Worksheet
SheetConnectionsheetINPUT("input.xls");
SheetConnectionsheetOUTPUT("output.xls");

// Constants
BigM = 1000000 ;

// Network node Paramaters
NbAllnodes from SheetRead(sheetINPUT,"parameters!B1:B1");
NbPlants from SheetRead(sheetINPUT,"parameters!B2:B2");
NbMixingCenters from SheetRead(sheetINPUT,"parameters!B3:B3");
NbRamps from SheetRead(sheetINPUT,"parameters!B4:B4");

// Time parameters
NbPeriod from SheetRead(sheetINPUT,"parameters!B5:B5");
L from SheetRead(sheetINPUT,"parameters!B6:B6");

c from SheetRead(sheetINPUT,"trp_cost!A1:K11");
u from SheetRead(sheetINPUT,"arc_capacity!A1:K11");
f from SheetRead(sheetINPUT,"arc_fixed_cost!A1:K11");
h from SheetRead(sheetINPUT,"carrier_shipment_fixed_cost!A1:K11");
tov from SheetRead(sheetINPUT,"transit_time!A1:K11");

s from SheetRead(sheetINPUT,"supply_demand!A1:C11");
I_zero from SheetRead(sheetINPUT,"initial_inventory!A1:A11");

p from SheetRead(sheetINPUT,"holding_cost!A1:A1");


X_PERIOD_1 to SheetWrite(sheetOUTPUT,"XRESULT!B2:L12");
X_PERIOD_2 to SheetWrite(sheetOUTPUT,"XRESULT!B15:L25");
X_PERIOD_3 to SheetWrite(sheetOUTPUT,"XRESULT!B28:L38");

R_PERIOD_1 to SheetWrite(sheetOUTPUT,"RRESULT!B2:L12");
R_PERIOD_2 to SheetWrite(sheetOUTPUT,"RRESULT!B15:L25");
R_PERIOD_3 to SheetWrite(sheetOUTPUT,"RRESULT!B28:L38");

Y_PERIOD_1 to SheetWrite(sheetOUTPUT,"YRESULT!B2:L12");
Y_PERIOD_2 to SheetWrite(sheetOUTPUT,"YRESULT!B15:L25");
Y_PERIOD_3 to SheetWrite(sheetOUTPUT,"YRESULT!B28:L38");

Q to SheetWrite(sheetOUTPUT,"QRESULT!B2:D12");
```

```
Transportation_Cost to SheetWrite(sheetOUTPUT,"COST!B1");
Transportation_Cost_P_M to SheetWrite(sheetOUTPUT,"COST!B8");
Transportation_Cost_M_R to SheetWrite(sheetOUTPUT,"COST!B9");
Transportation_Cost_M_M to SheetWrite(sheetOUTPUT,"COST!B10");
Transportation_Cost_P_R to SheetWrite(sheetOUTPUT,"COST!B11");

Fixed_Cost_ARC to SheetWrite(sheetOUTPUT,"COST!B2");
Fixed_Cost_ARC_P_M to SheetWrite(sheetOUTPUT,"COST!B13");
Fixed_Cost_ARC_M_R to SheetWrite(sheetOUTPUT,"COST!B14");
Fixed_Cost_ARC_M_M to SheetWrite(sheetOUTPUT,"COST!B15");
Fixed_Cost_ARC_P_R to SheetWrite(sheetOUTPUT,"COST!B16");

Fixed_Cost_PerShipment to SheetWrite(sheetOUTPUT,"COST!B3");
Fixed_Cost_PerShipment_P_M to SheetWrite(sheetOUTPUT,"COST!B18");
Fixed_Cost_PerShipment_M_R to SheetWrite(sheetOUTPUT,"COST!B19");
Fixed_Cost_PerShipment_M_M to SheetWrite(sheetOUTPUT,"COST!B20");
Fixed_Cost_PerShipment_P_R to SheetWrite(sheetOUTPUT,"COST!B21");

Inventory_Holding_Cost to SheetWrite(sheetOUTPUT,"COST!B4");
Inventory_Holding_Cost_Plant to SheetWrite(sheetOUTPUT,"COST!B23");
Inventory_Holding_Cost_MC to SheetWrite(sheetOUTPUT,"COST!B24");
Inventory_Holding_Cost_Ramp to SheetWrite(sheetOUTPUT,"COST!B25");

In_Transit_Inventory_Cost to SheetWrite(sheetOUTPUT,"COST!B5");
In_Transit_Inventory_Cost_P_M to SheetWrite(sheetOUTPUT,"COST!B27");
In_Transit_Inventory_Cost_M_R to SheetWrite(sheetOUTPUT,"COST!B28");
In_Transit_Inventory_Cost_M_M to SheetWrite(sheetOUTPUT,"COST!B29");
In_Transit_Inventory_Cost_P_R to SheetWrite(sheetOUTPUT,"COST!B30");
```

APPENIX B: MATLAB CODES FOR LOST SALES AND EXPEDITED SHIPMENTS

B-1: Main Model (main.m)

```
% simulation
no_simulations=input('Number of samples to be generated for each scenario=')
begin=input('Enter beginning row= ')
ending=input('Enter ending row= ')
Regular=[];
Expedited=[];
Lost=[];
scenarios=xlsread('els.xlsx','Sheet1','scenarios');
Regular=zeros(ending-begin+1,no_simulations);
Expedited=zeros(ending-begin+1,no_simulations);
Lost=zeros(ending-begin+1,no_simulations);
for i=1:1:ending-begin+1
   x1=scenarios(i,2)
   r1=scenarios(i,3)
   x2=scenarios(i,4)
   r2  =scenarios(i,5)
   offset1 =scenarios(i,6)
   offset2 =scenarios(i,7)
x_out =scenarios(i,8)
   L =scenarios(i,9)
   PT =scenarios(i,10)
   ET  =scenarios(i,11)
   Inv0=scenarios(i,12)
Regular_temp=0;
Expedited_temp=0;
Lost_temp=0;

   for k=1:1:no_simulations

[Regular_temp,Expedited_temp,Lost_temp]=ELS(x1,r1,x2,r2,offset1,offset2,x_ou
t,L,PT,ET, Inv0);
      Regular(i,k)=Regular_temp;
      Expedited(i,k)=Expedited_temp;
      Lost(i,k)=Lost_temp;
   end
end
xlswrite('ELSoutput.xlsx',Regular,1)
xlswrite('ELSoutput.xlsx',Expedited,2)
xlswrite('ELSoutput.xlsx',Lost,3)
```

B-2: Expected Lost Sales Model (<u>ELS.m)</u>

```
function [Regular,Expedited,Lost]=ELS(x1,r1,x2,r2,offset1,offset2,x_out,L,PT,ET,
Inv0)
% clear all
% global L
% global dbtws1 offset1
% global dbtws2 offset2
% global x1 r1
% global x2 r2
% global demand
% global Inv0
% %
% L=20;  % no of days
% PT=2;  % customer patience
% ET=4;    % expediting threshold
%
% Inv0=0
% x1=10
% r1=3
% offset1=0
%
% x2=10
% r2=2
% offset2=0
% x_out=5;

% generate the demand
demand=poissrnd(x_out,1,L-1)';

temp=sum(demand);
if temp<= 100
   demand=[demand; 100-temp];
else
   demand=floor(100*demand/temp);
   demand=[demand; 100-sum(demand)];
   if demand(end)>=1.5*x_out
distlist=ceil(rand(floor(demand(end)-1.5*x_out),1)*20);
      demand(end)=demand(end)-length(distlist);
      demand(distlist)=demand(distlist)+1;
      demand(end)=demand(end)+ 100-sum(demand);
   end
end
```

```
demand;
temp=sum(demand);

dbtws1=floor(L/r1);
dbtws2=floor(L/r2);
% finding the cumulative inventory
CumInv(1)=Inv0;
Add_Shortage_PerUnitTime=[];

[CumInv,
Add_Shortage_PerUnitTime]=CumInv_AddShortage(demand,dbtws1,offset1,dbt
ws2,offset2,x1,r1,x2,r2,L,Inv0);
Add_Shortage_PerUnitTime=abs(Add_Shortage_PerUnitTime);

BT=backorder(L,CumInv);

% temp1=demand'
% temp2=CumInv'
% temp3=Add_Shortage_PerUnitTime'
% temp4=BT';

Back_Regular=zeros(L,1);
Back_Expedite=zeros(L,1);
Back_Lost=zeros(L,1);

temp_demand=demand;
CumInv_temp=CumInv;
Add_Shortage_PerUnitTime_temp=Add_Shortage_PerUnitTime;
for i=1:1:L
   if BT(i)>0
      if BT(i)>ET % lost sale candidate
Back_Lost(i)=Add_Shortage_PerUnitTime_temp(i);
temp_demand(i)=temp_demand(i)-Add_Shortage_PerUnitTime_temp(i);
         [CumInv_temp,
Add_Shortage_PerUnitTime_temp]=CumInv_AddShortage(temp_demand,dbtws
1,offset1,dbtws2,offset2,x1,r1,x2,r2,L,Inv0);

Add_Shortage_PerUnitTime_temp=abs(Add_Shortage_PerUnitTime_temp);
elseif BT(i)>PT && BT(i)<=ET  % expediting
Back_Expedite(i)=Add_Shortage_PerUnitTime_temp(i);
elseif BT(i)<=PT %regular back order
Back_Regular(i)=Add_Shortage_PerUnitTime_temp(i);
      end
   end
```

```
   BT=backorder(L,CumInv_temp);
end
Regular=sum(Back_Regular);
Expedited=sum(Back_Expedite);
Lost=sum(Back_Lost);


function [BT]=backorder(L,CumInv)

% Backorder time
BT=zeros(L,1);
counter=0;
for i=L:-1:1
   if  CumInv(i)<0
      counter=counter+1;
      BT(i)= counter;
   else
      counter=0;
   end
end

function [CumInv,
Add_Shortage_PerUnitTime]=CumInv_AddShortage(demand,dbtws1,offset1,dbt
ws2,offset2,x1,r1,x2,r2,L,Inv0);
CumInv=zeros(L,1);
Add_Shortage_PerUnitTime=zeros(L,1);
for i=1:1:L
   if mod(i+offset1,dbtws1)==1 && ceil(i/dbtws1)<=r1
      ship1=1;
   else
      ship1=0;
   end
   if mod(i+offset2,dbtws2)==1 && ceil(i/dbtws2)<=r2
      ship2=1;
   else
      ship2=0;
   end

   Inflow=ship1*x1+ship2*x2;
   Outflow=demand(i);
   if i==1
CumInv(i)= Inv0+Inflow-Outflow;
   else
CumInv(i)= CumInv(i-1)+Inflow-Outflow;
```

```
    end
    if i>1 &&CumInv(i)<0
        if CumInv(i-1)<=0  && (+Inflow-Outflow)<0
Add_Shortage_PerUnitTime(i)=+Inflow-Outflow;
elseifCumInv(i-1)>=0 && (+Inflow-Outflow)<0
Add_Shortage_PerUnitTime(i)=CumInv(i-1)+Inflow-Outflow;
        end
    end
%     CumInv=CumInv';
%     Add_Shortage_PerUnitTime=Add_Shortage_PerUnitTime';
end


%
% function [BT]=backorder(L,CumInv)
%
% % Backorder time
% BT=[];
% counter=0;
% for i=L:-1:1
%     if  CumInv(i)<0
%         counter=counter+1;
%         BT(i)= counter;
%     else
%         counter=0;
%     end
% end
% BT;
```

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ABSTRACT

A COLLABORATIVE FRAMEWORK IN OUTBOUND LOGISTICS FOR THE US AUTOMAKERS

by

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December 2011

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In this new competitive era, cross-company collaboration in product development, standardizing and communizing supply base, sharing flexible manufacturing platforms, using common inbound and out bound logistics service providers and warehousing etc. offer great opportunities for the US automakers to reduce overall cost and return to profitability. The collaboration in the intra- and inter-OEM outbound logistics operations is a critical area that the US automakers need to pay attention and prioritize in their cost reduction initiatives. Through the horizontal collaboration in the outbound logistics operations, these companies can deliver finished vehicles to their customer at the optimum cost levels which cannot be achieved in isolation. The optimization of outbound logistics operations through consolidation and collaboration among OEMs has tremendous potential to contribute to the profitability by lowering the cost of transportation, in-house inventory, transportation time, and facility costs.

This research presents an integrated collaboration framework for the outbound logistics operations of the US automakers. In our framework, we propose three levels for the US automakers to form outbound logistics collaboration: operational, tactical, and strategic. We developed a capacitated multi-commodity multi-period minimum cost network flow (MCNF) model with frequency based shipments. We developed new models for inventory, lost sales, and expedited shipments and integrated in the MCNF model. Resulting baseline model is then reformulated through the novel linearization approaches for computational tractability. Operational, tactical, and strategic collaboration adaptations are developed using the baseline model. Stylized experiments are conducted for sensitivity analysis and a case study based on two major US automotive OEMs is performed for demonstration of the benefits. Our research results indicate that collaboration at all levels improves the delivery and cost performance of the Outbound Logistics Network Systems.

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Certified Six Sigma Blackbelt
Certified Lean Manufacturing Engineer from University of Michigan, Ann Arbor, MI

EXTRA-CURRICULAR ACTIVITIES

President, Bangladeshi American Democratic Caucus (2009-)
Vice President, Morningside Student Government, Sioux City, IA (1994-1996)
Chairman, Morningside College Activities Council, Sioux City, IA (1992-1993)
President, International Student Organizations, University of Nebraska, LN (1994-1996)

PUBLICATIONS

- Murat, Alper, Leslie, Monplaisir, Chinnam, Ratna, Babu, Yaprak, Atilla, Hassan, Nazmul, "Collaborative Framework for Outbound Logistics." Manuscript under preparation for submission.
- Murat, Alper, Hassan, Nazmul, Tagavi, Ali, "Multi-period, Multi-product MCNF problem for Automotive Outbound Logistics Network." Manuscript under preparation for submission.
- Murat, Alper, Hassan, Nazmul, "A Case Study for Collaborative Vehicle Outbound Logistics Systems."Manuscript under preparation for submission.