Development of a Tool to Assess Effectiveness of Intermodal Facility Locations and Designs

Final Report

by

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16. Abstract

This study is focused on the design and operation of a freight network that supports horizontal carrier collaboration where two or more carriers form an alliance and share pick-up and delivery of jobs. In carrier collaboration, it is assumed that carriers are allowed to retain some of the pickup and delivery jobs they receive from clients while releasing the rest of the jobs to a common pool. Two models are developed: one for strategic planning and one for operations. The objective of the multi-period strategic model is to determine the number and location of intermodal terminals (IMTs) that minimize the total relevant transportation and operational costs, given a set of constraints like ensuring all pickup/delivery demands to/from customers are met, budget, and a limited set of candidate IMT locations. The objective of the operational model is to jointly determine the optimal allocation of jobs from the common pool to the carriers and pickup/delivery routes for each truck. Numerical experiments are conducted using hypothetical networks for both models. Findings from the strategic model indicates that allowing the IMT's to hold some inventory for a few periods of time provides network flexibility that avoids the need to open additional IMT's and reduces the need to use high-cost direct shipping to meet demand. Findings from the operational model confirm expectation that carrier collaboration/coordination can yield significant reduction in total cost of serving all pickup and delivery jobs. The amount of reduction depends on the number and location of pickup and delivery jobs that are shared between carriers.

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EXECUTIVE SUMMARY

The aim of this project is to develop models to improve freight logistics in South Carolina. Two types of models were developed: 1) a strategic model for locating intermodal terminals (IMT) in a freight transportation network, and 2) an operational model for scheduling pickups and deliveries with horizontal collaboration.

Strategic model for locating intermodal terminals

The results from a hypothetical intermodal freight network indicate that, operating under a limited budget critically impacts the intermodal shipping share and thus the total network cost. Short term inventory at IMTs gives the freight network flexibility where it can meet the demands for different periods of time in a more cost-efficient manner. As volume of the freight products increases the network increases the inventory utilization of IMTs and utilization of a mode depends on the lower transportation cost and availability of the mode. Higher volume capacity modes reduce the total network cost and increase the mode utilization as it provides better economies of scale. Also, the results show that total network cost and intermodal shipping share improve if an intermodal network offers higher capacity modes with higher availability.

Operational model with horizontal collaboration

Results from numerical experiments indicate that collaboration yielded lower cost. The cost reduction with collaboration depends on the locations of pickup and delivery nodes, number of retained jobs, and location of pickup or delivery nodes of retained jobs. The total cost reduction with collaboration is 22% to 28% when each carrier retains 10% of their jobs. When carriers retain 70% of their jobs, the cost reduction decreases to 18% to 23%.

CHAPTER 1
Introduction

The complex systems that facilitate the movement and handling of the nation's goods have historically driven the prosperity and quality of life in the U.S. Every day, 6 million people work to move 48 million tons of freight valued at over $46B (Gue 2014). The total impact of material handling and logistics on the economy is measured in trillions of dollars annually. Freight transportation is especially important in South Carolina that has major seaports, airports, inland ports, rail lines and many interstate highways connecting major population centers. Further, there is nothing to suggest that freight transportation will not remain a vital component of the US economy as well as that of South Carolina. There are, however, several environmental factors that are stressing the freight transportation and logistics systems that could create serious negative impacts.

The Material Handling and Logistics U.S. Roadmap [Gue 2014] identified some important trends that are taxing the current logistics and transportation systems including the growth of e-commerce, relentless competition, mass personalization, urbanization, mobile and wearable computing, robotics, and automation, sensors and the Internet of Things (IoT), data analytics, the changing workforce, and sustainability.

Simultaneously, overall freight is growing as is the fraction of that freight that is attributed to eCommerce. The US freight transportation system moved nearly 17 billion tons of freight in 2012, 18 billion tons in 2015 and is expected to have a demand for 25.3 billion tons in 2045 (Transportation Statistics Annual Report, 2017). In South Carolina, the increase in total freight in tons from 2015 to 2016 is 6.18% (Freight Analysis Framework, 2019). Between 2012 and 2016, the fraction of retail attributed to eCommerce grew from 7.9% to 11.7% (Fernandez 2017).

In addition, the current freight transportation system and strategy are not efficient. The logistics systems used to move and handle goods in the U.S. are inefficient and unsustainable. In 2007, it was estimated that about 25% of truck miles were driven with empty or near-empty trailers and the remaining 75% were less than 60% full resulting in average trailer fullness of approximately 45% (Matthams, 2012) (McKinnon 2010). As a result, more than 7B gallons of diesel fuel were used to ship truckloads of air, often only to reposition assets. In addition, road congestion is an increasing problem for urban areas as well as heavily traveled rural interstates.

While there are many impacts that these changes are inducing, two that this research begins to address are: 1) increasing the amount of freight into a current system/strategy that seems to have systemic inefficiency and 2) the growth of eCommerce is creating more points in the first and last mile distribution networks. This project considers two strategies to improve the freight transportation system that are both based on collaboration/consolidation and both are especially applicable to South Carolina, namely: 1) more efficient transport of the increasing amount of freight by locating and using intermodal terminals (IMT), and 2) more efficient first and last mile logistics using horizontal collaboration among providers.

A strategic approach is taken to address more efficiently transporting of an ever-increasing amount of freight by looking at use of intermodal transportation. Intermodal transportation creates a synchronization between more expensive but faster and more flexible modes like trucks and less-expensive but slower and less flexible modes like rail

(Groothedde et al., 2005). In fact, intermodal transportation can be more cost effective, energy efficient, and can have better performance than the unimodal option (Huynh et al., 2013, Lammagard, 2012). However, the degree of economic and other benefits associated with intermodal transportation depends on many factors including type, location and number of intermodal terminals and the services provided by the intermodal terminals (Steele, 2011, Sorensen et al., 2013). In particular, the number and locations of IMT's can determine if the network is efficient and cost-effective or inefficient and underutilized or overloaded.

Therefore, determining the number intermodal terminals to use in a network and locating them are critical decisions. At a high level, this decision is not terribly complicated. If the benefits of opening and operating an IMT exceed the initial capital expenditure required for setup plus the operating costs to facilitate the required material handling, then the IMT is opened. If not, then the IMT should not be opened. The real problem, however, is very complicated. First there are many factors and costs involved in this trade-off. Second, the decision on all possible IMT's and locations must be made simultaneously. The freight movement through any IMT is highly dependent on the location of other IMT's. In addition, the problem is dynamic even if it is thought of as a series static decision on when to open IMT's and what their capacities are. Also, the decision to open or not open an IMT is done with limited resources because; in reality, there is never an unlimited budget.

To address this strategic decision, a mixed integer programming model has been developed. It combines features of the facility location problem and freight consolidation. The freight transportation network consists of potential IMT's, suppliers with known locations and available quantities, customers with known locations and demands, two types of trucks with different capacities, and rail. Trucks can direct ship from supplier to customer or interact with an IMT. Rail or truck can carry freight between IMT's. An interesting addition that has been added is the ability for each IMT to hold a limited amount of freight for a short period of time so short-term imbalances can be accommodated and the model has opportunity to more intelligently consolidate freight. For added realism, the network carries multiple products, each with a unique volume. Customers can specify which supplier must satisfy an order or that is can be satisfied by any supplier.

Improving first and last mile delivery efficiency is also accomplished using consolidation/collaboration; however, in this case it is "horizontal" collaboration. This occurs when organizations at the same echelon in a supply chain, such as shippers or carriers, work together improve efficiency and reduce hidden costs (Ergun et al., 2007b). This is different form vertical collaboration that occurs when organizations at different levels work together which is frequently done when a large company (e.g., Walmart and Toyota) established relationships with suppliers and transportation partners (Ergun et al., 2007b).

Horizontal collaboration is an emerging trend in logistics because it often involves collaboration among competitors because it can provide significant benefits for both; however, it is now widely used. There are many reasons with the vast majority involving the obvious hesitance of not sharing information with a competitor because of lack of trust. This is particularly unfortunate in trucking because companies operate in a very competitive market which has translated into small profit margins. It is difficult for small and medium sized carriers to reduce their operational cost further (Wang, 2014);

however, this industry segment could realize significant benefits from horizontal collaboration (Dai et al., 2012). This is especially true for carriers that operate using less than truckload (LTL); therefore, this study centers on collaboration of LTL carriers under centralized planning.

Carrier collaboration under centralized planning involves a collaborative alliance of carriers that fulfil pickup and delivery jobs based on a performance objective like total distance traveled to complete all jobs rather than each carrier fulfilling jobs they receive. In this system, carriers still receive jobs and they are allowed to retain some number for themselves; however, the remainder are aggregated in a common pool from which a central authority determines the optimal allocation for each carrier. This leads to two research problems. First is optimally allocating of jobs in the common pool to each carrier in the alliance. Second is determining of optimal route for each carrier to execute the allocated jobs. The second part of the problem is a variant of vehicle routing problem with pickup and delivery. This class of problems has been studied extensively with different formulations that invoke a variety of assumptions because of its complexity. Unfortunately, some of these assumptions are quite different from practice so for a study intended for eventual implementation, some common assumptions must be relaxed. Therefore, the LTL carrier collaboration routing problem is formulated as follows. Each job consists of a pickup location and a corresponding delivery location, and each location has a time window for pickup or delivery. Each carrier in the alliance will have a depot where trucks start and end trips. One truck cannot serve all jobs received by a carrier because the maximum hour of continuous service of a truck driver is restricted to 14 hours as per Federal Motor Carrier Safety Administration (Federal Motor Carrier Safety Administration, 2019). Therefore, multiple vehicles may send from each depot to ensure that all jobs are served. The pickup location should be visited before the corresponding delivery location by the same vehicle. Each vehicle will have a maximum capacity limit which makes the problem a capacitated problem.

The objectives of this study are to:

1) Develop a strategic model to determine the number and location of IMTs that minimize the total relevant transportation and operational costs, given a set of constraints like ensuring all pickup/delivery demands to/from customers are met, budget, and a limited set of candidate IMT locations.
2) Develop an operational model for an LTL carrier collaboration problem to determine the optimal allocation of jobs from the common pool to the carriers and pickup/delivery routes for each truck.

The next chapter (Chapter 2) presents a literature review of related work. Chapter 3 describes the methodology used to develop both the strategic and operational models. Chapter 4 presents the results and findings from the mathematical models. Lastly, Chapter 5 presents this study's summary and conclusions.

CHAPTER 2
Literature Review

A detailed literature review of intermodal terminal and carrier collaboration is done in this section. The type, design and location of IMT are the major factors affecting the operational efficiency of intermodal transportation, (Allen et al., 2012, Bontekoning, 2000). Therefore, the literature review on intermodal transportation has been done in two sections: (i) study on types of intermodal terminals and their design characteristics, (ii) literature review of optimal IMT location problems.

2.1 Types of intermodal terminals and their design characteristics

A background study on types, factors influencing the type and design and the transshipment requirements of the intermodal terminals are provided in this section.

Based on location and the requirements of equipment, the intermodal terminals are classified into three such as port terminal, inland rail terminal and distribution centers. A port terminal can be either a container sea terminal, an intermediate hub terminal or a barge terminal. There are five different types of rail intermodal terminals such as on-dock, near dock, trans-modal terminal, load center and satellite terminal. There are three different types of distribution centers such as transloading, cross-docking and warehousing. See (Rodrigue et al., 2016) and (Notteboom et al., 2018) for more information about each type of intermodal terminal.

Middendorf (1998) discussed various factors governing the classification and types of intermodal terminals. The authors state, the intermodal terminals can be grouped into six according to the five dimensions such as mode pairs, type of cargo, type of transfer, private or public ownership and the availability for public use. They are trailer-on-flatcar/container-on-flatcar, auto terminal, truck-rail bulk transloading facilities, truck-rail reload facilities, liquid bulk terminals, grain terminals and waterway intermodal terminals.

Based on the function of terminal in the intermodal network, the intermodal rail road researchers identified four types of rail-road intermodal terminals (Behrends, 2011). They are start and end terminals, intermediate terminals, hub terminals and spoke terminals. Start and end terminal usually handles a large volume of freight, which are split into smaller flows for further transport on road, however, the performance requirements on the transshipment technology are moderate. Intermediate terminals handle only a limited number of unit-loads which must be distributed at the terminal region. Here the demand for improvement in the transshipment technology is comparably high. Hub terminals are not intermodal terminals instead it provides transshipment of loads between different trains. Both the transshipment capacity and technology are very important in hub terminals because this terminal handle extensive throughput of unit loads. The spoke terminal consolidated small volumes of load units into bigger flows. However, the total load units handled is limited therefore, the transshipment technology requirements are comparatively low.

Woxenius (2007) studied how the transportation network design influencing the type, design, capacity requirements and choice of transshipment technology at rail- road IMT. They described how the afore-mentioned varies with the most common six alternative transport network designs (direct link, corridor, hub-and-spoke, connected hubs, static routes and dynamic routes). The suggested terminal types for each type of network are: for the direct link design, end terminal is suitable however, end terminal and intermediate terminal is suitable for corridor link design. Hub terminal and spoke terminal are suitable for both hub-and-spoke and connected hub design. Exchange terminal and gateway are suitable for static routes design. For dynamic routes the suitable type of terminal is the exchange terminal.

The design requirements for terminals corresponds to each transport network type of which there are several (Woxenius, 2007). In *direct link design*, all unit loads in the train are transshipped thus the terminal capacity requirement is limited. This design is complicated because of the large number of unit loads handled at the terminal. In *corridor design*, the number of unit loads handled is limited; therefore, the capacity requirement is moderate. The design objective here is that the transfer time should be minimum. Providing optional storage space in this design can be effective as well. The design of a terminal should be optimally decided to simultaneously provide fast transfer and minimum fixed cost. In *hub-and-spoke design*, all unit loads pass through the hub terminal; hence, the hub terminal requires a large capacity. Further, the whole system is adversely impacted if the hub terminal is not reliable. As might be expected, there is a great need for intermediate storage. In *connected hubs design,* only a limited number of trains are connected through the hubs so the capacity requirements are moderate. Static routes are often used for intermodal transport or when time demands are flexible. If the terminal along the static routes is not a gateway terminal, the transshipment capacity required is limited. In dynamic routes the terminal requirements are like static routes. However, there is a greater need for flexibility as the operations change between each transport cycle.

Intermodal transportation is the widely preferred option for inland freight distribution due to its large capacity, less energy consumption, low cost, contribution to reducing road congestion and environmental reasons (Zumerchik et al., 2012). However, the transfer delay at IMT would lead to the overall delay in product delivery, missing of connections and damage of products. With substantial improvement in the IMT design and operations the operational performance of the IMT can be greatly enhanced, (Rodrigue et al., 2009). The author says, goods movement will remain dominantly serviced by trucking over increasingly congested highways if substantial improvements are not made to intermodal transportation. Quick handling time at the terminals will give more time at the link which improves the efficiency of freight transportation. All the above-mentioned facts show the necessity of improving the performance of IMT.

Only a few studies have been published that assess the ability of technologies to improve the operational performance of IMTs. Bontekoning (2000) discussed several new generation terminal designs which can significantly reduce the transfer delay at terminals and thereby reduce the total time and cost of intermodal freight transportation. Bontekoning et. al. (1999) defined the new generation terminal as the terminal which uses automation and robotization, integrated operations, and compact layout. The new generation terminal and new rail transshipment technologies make the intermodal freight transportation more competitive. This research also listed a number of rail-road terminal design concepts that can be considered as new generation terminals. They are: (i) Noell Megahub, (ii) Commutor, (iii) Krupp Rendezvouz terminals Megahub, Highrack, Compact and Small, (iv) Noel1 SUT 1200 and SUT 400, (v) Transmann Handling Machine, (vi) Tuchschmid Compact Terminals. Finally, the study noted advantages of new generation terminals over conventional terminals. These include reduction in the transshipment cost (and time) due to more efficient operations and reduction in the costs (and time) on the link due to more sophisticated bundling.

Zumerchik et al. (2012) argued that Automated Transfer Management System (ATMS) at terminals could significantly improve operational efficiency and economics of both long haul and short haul intermodal movements, including port shuttle trains. ATMS helps providing a better synchronization of multiple modes having different operational and technical characteristics. Application of ATMS at intermodal terminal includes, trackside at rail terminal, vessel loading /unloading, chassis flip, port stack container yards, chassis storage and loading bays at distribution centers.

Several marine terminals have been converted into automated terminal world-wide. The Rotterdam marine terminal is the first automated terminal that is opened in 1993 (Port automation, 2018). Now the largest automated terminal started operation at Shanghai, China (Largest Automated Container Terminal Starts Operations, 2018).

2.2 Models for locating intermodal terminals

According to Teye et al. (2017) Intermodal Terminal Location Problems (IMTLP) can be considered as an extension of the classical Hub Facility Location Problems (HFLP). The hub location problems first started to gain attention after the seminal work by O'Kelly (1986a,1986b,1987). O'Kelly (1987) introduced the single allocation p-hub median problems using a model based on quadratic integer programming. Later, the first linear integer programming based multiple allocation model was given by Campbell (1992). The intermodal hub location problem was first introduced by Arnold et al. (2001), who proposed a mixed integer programming (MIP) model that minimized the fixed costs for opening of IMTs and variable costs for unimodal and intermodal transportation and was later improved in a work by Arnold et al. (2004). These studies laid out the foundation for further research in intermodal terminal location-allocation problems, after which there has been a significant growth in the related research work in the last three decades.

Ishfaq et al. (2011) developed a multiple allocation p-hub median model for road-rail intermodal transportation network which considered different fixed costs for opening new hubs depending on their location and modal connectivity along with time service constraints. A tabu search meta-heuristic was used to obtain solutions for large sized problems. Meng et al. (2011) presented an intermodal hub and spoke network design problem which considered multi-type containers and multiple stakeholders: the network planner, carriers, hub operators and intermodal operators and was solved using a hybrid genetic algorithm. Alumur et al. (2012) developed a linear mixed integer linear programming (MILP) model that considered jointly transportation costs and travel times and is solved using a heuristic.

Sorensen et al. (2013) adapted the original model presented in Arnold et al. (2001) to develop a bi-objective problem considering the different stakeholders. The model used two objective functions which minimized transportation cost from the network users' perspective and location cost from the terminal operator's perspective. Serper et al. (2016) developed a MIP model which designed an intermodal hub network and considered different types of vehicles available. Their model also determined that how many vehicles of a type should be purchased and between which hub pairs to operate them. Teye et al. (2017) formulated a non-linear mixed integer linear programming model.

The model solves the facility location problem but also gives the shippers a choice, whether to use an IMT or not.

All the works that we have discussed so far do not consider the multi-period aspect in their models. The multi-period aspect has been getting significant attention in the recent times as it is more pragmatic. The seminal work in multi-period (or dynamic) hub location was proposed by Campbell (1990), in which he proposed a continuous approximation model for hub location with demand growing over time. Contreras et al.(2011a) presented a dynamic uncapacitated hub location problem where total cost was minimized over the planning horizon and the hubs could be opened or closed in a time-period. Serper et al. (2016) proposed a multi-period MILP model with both szingle and multiple allocations and where capacities could be expanded gradually over time. According to Serper et al. (2016) they were the first to consider hub capacities in a multi-period model. Some work has been done where different scenarios (transportation costs, demands, capacities, etc.) have been assumed to be stochastic. Contreras et al.(2011b) proposed a stochastic model for hub location with uncertain demands and transportation costs. Fotuhi et al. (2015) proposed a stochastic model for competitive IMT location problem with uncertain demands. In our study, we consider the demands to be forecasted beforehand and thus model is deterministic. We also assume that the IMTs can hold inventory over a few time periods. A similar approach was used by Bhattacharya et al. (2014) but not in a multi-period setting.

Based on the literature review, following areas were identified as significant for research: (1) IMT location-allocation, (2) routing decisions, (3) mode selection (4) multi-period planning (5) mode volume capacity (6) product volume (7) inventory at IMTs

2.3 Models that consider horizontal collaboration of carriers

The literature most relevant to this study centers on carrier collaboration so the following review is focused on the sub area of collaborative logistics. The literature on carrier collaboration has many dimensions. The papers reviewed in this section have similarities, but each addresses a specific problem. There are three approaches to carrier collaboration (Gansterer et al., 2017): centralized collaborative planning, decentralized panning without auction, and decentralized planning with auction. As the name implies, centralized collaborative planning relies on a central authority to make all decisions. The key is that all information about the carriers and shipments are shared. While centralized planning is likely to produce the best solutions, it may not work if one or more of the collaborators are not willing to share full information. In this case, the decentralized approach has been utilized using auction-based or non-auction-based approaches.

The preliminary studies on carrier collaboration dealt with reduction of empty truck backhauls. For example, Ergun et al. (2007a) provided an important early contribution on carrier collaboration where their work centered on identifying repeatable, dedicated, continuous truck load tours to minimize truck repositioning. The mathematical model is a time-constrained lane covering problem which was formulated as a set covering problem. Their wok involved the collaboration of truck load (TL) carriers. Later, the less than truckload carrier collaboration (LTLCC) problem has received considerable attention. Nadarajah et al. (2008) introduced a two stage solution methodology for LTL collaboration. The first stage models the collaboration between multiple carriers at the entrance of the city as a vehicle routing problem with time windows. The second stage model includes collaboration between carriers at transshipment facilities while executing their routes in the first stage. This model is solved using a local search heuristic. Their numerical study indicated that collaborating at the entrance of the city reduced the total distance travelled by 7 to 15% while the intra-city collaboration further reduced the distance by 3 to 15%. Nadarajah et al. (2013) continued this basic idea with a three-phase approach. The first phase is again the entry point collaboration that is modeled as a vehicle routing problem. The second phase uses a quad-tree search to locate facilities and the third phase employs a greedy local search to build collaborative routes. Numerical experiments using this approach indicated that collaboration reduces route distance by 12% and travel time by 15%. Their (Nadarajah et al., 2008, Nadarajah et al., 2013) work is different from ours as they considered the exchange of customers (destination points) between carriers at the entrance of a city but we have considered the exchange of pickup and delivery jobs between the carriers in a collaborative alliance. Dai et al. (2012) developed a mathematical model to determine the optimal vehicle tours for pickup and delivery when shippers collaborate to share their carrier's vehicle capacity for LTL transportation and solved it using Lagrangian relaxation.

Decentralized method is approached in several studies such as Dai et al. (2011), Dai et al., (2014), Li et al. (2016), Berger et al. (2010) and Hernandez et al. (2011). Dai et al. (2011) proposed a multi-agent, auction-based framework for carrier collaboration in LTL transportation using decentralized planning with auction. The objective function was to maximize the total profit of the alliance. In their scenario, the carriers act as the auctioneer when they want to outsource a request and they act as a bidder when they want to acquire a request. Another study of Dai et al. (2014) proposed a multi-round pricing-setting based combinatorial auction approach to solve a carrier collaboration problem with pickup and delivery in decentralized approach. Li et al. (2016) investigated a slightly different problem that was rooted in the pickup and delivery problem with time windows by including total profit and retained job. Here, several carriers form an alliance to maximize the total profit of the alliance as well as the carriers, but each carrier has retained jobs that will be served by the same carrier and selective jobs that will be served by other carriers in the alliance. Their model determines the selective jobs and the optimal vehicle routes for each carrier with decentralized planning. Another decentralized planning and auction scenario was reported by Berger et al. (2010) in which the objective was to maximize the profit of the alliance without decreasing the individual profit of the carriers. Comparisons were made with the non-collaboration scenario and centralized planning scenario. They concluded that centralized planning has more potential to improve the network profit than either the decentralized or no-collaboration scenarios. Hernandez et al. (2011) proposed a deterministic dynamic single carrier collaboration problem (DDSCCP) to analyze the potential benefit of carrier-carrier collaboration for the small to medium sized LTL carriers. A multi-commodity minimum cost flow model for DDSCCP was developed and solved it using a branch and cut algorithm.

Centraized planning is adopted in some studies such as Krajewska et al. (2008) and Gansterer et al. (2018). Krajewska et al. (2008) discussed a carrier collaboration problem where carriers share all received jobs. They assumed that each carrier has only one vehicle to serve all jobs. They have also done a profit allocation to the carriers using cooperative game theory. They haven't provided a mathematical model for this problem; however, they solved the model using adaptive large neighborhood approach. Our work is different from theirs because we specifically considered LTL transportation and allow carriers to retain certain jobs. In addition, ours is a capacitated vehicle routing problem with pickup and delivery and have multiple vehicles at each carrier depot by restricting the maximum hour that a vehicle can service in one vehicle route. We have developed a mathematical model to solve the problem. Gansterer et al. (2018) addressed the pickup and delivery problem in LTLCC with centralized collaborative planning as a travelling salesman problem. They used the concept of Hamiltonian tour formulation as suggested by Lu et al. (2004) where the destination depot of one vehicle is the departure depot of the next vehicle. With this concept, the time window cannot be considered, and they also assumed that there is only one vehicle at each carrier depot. They solved a small network which consists of 3 carrier depots and 9 requests for each carrier by using bender's decomposition, column generation and branch and cut. Bender's decomposition was superior to both branch and cut, and column generation.

Even though few studies have been done to address the carrier collaboration problem under centralized planning, those are not considered most of the real-world constraints in their problems which is very important when we use the model to solve a real-world problem. Specifically, pickup and the corresponding delivery by the same vehicle, mixed pickup and delivery in one single route, job retention by the carriers, time-window, multiple vehicle routes at each depot in order serve all the pickup and delivery jobs received, restriction on maximum hour for each vehicle route and vehicle capacity. Therefore, a LTLCC problem in centralized planning is modelled as a multi-depot pickup and delivery problem that does not violate all the above-mentioned constraints.

CHAPTER 3
Methodology

The following provides the methodologies used for the strategic and operational models.

3.1 Intermodal terminal location problem

3.1.1 Problem definition

Intermodal transportation involves the transportation of freight from the origin to destination without repacking of goods in-between and the transfer and change of mode of transport takes place only at the IMTs. The intermodal terminal location problem locates IMTs out of a set of candidate locations while minimizing the total relevant network cost which includes the fixed cost to open an IMT, fixed cost to operate a mode on intermodal link, transportation costs, loading/unloading costs and inventory holding costs. The freight transportation for shorter distances is usually carried out by trucks, truck transports from a shipper to a nearby IMT is called prehaul, whereas the transportation from an IMT to a nearby consignee is called endhaul.

We assume three type of freight flows in the study as illustrated in Figure 3.1: (1) direct shipping from supplier to customer, (2) intermodally from supplier to customer via a pair of IMTs, (3) supplier to customer via an intermodal hub. The latter two flow types combined are considered as the net flow through the intermodal network in our study. We design this model to build up a new network and do not consider the existing terminals for capacity expansion. The hub nodes are potential candidates for being opened in a time-period and if opened in a time-period, they stay open for the succeeding time-periods. The non-hub nodes can either be shipper or consignees or both.

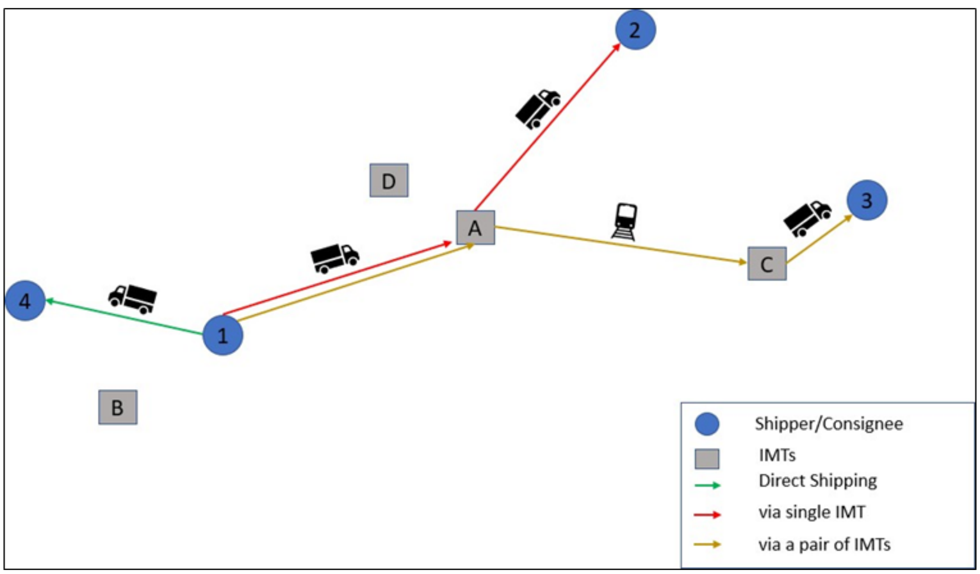

Figure 3.1: Possible freight flows in the network.

We have considered different freights (products) types with different volume and all the modes have a space (or volume) limitation with a limited number of trips available between any two nodes. The IMTs have a throughput capacity (freight handling capacity), which includes both inbound and outbound flows. An allocated budget to open IMTs is considered for the entire planning horizon. The IMTs can hold inventory over a few periods, but unloading, holding and loading costs are incurred in this process. The consignees can demand specific freight type from a specific shipper or raise a free demand (i.e. freight from any shipper can satisfy this demand).

We made a few other assumptions in our model: (1) The goods transfer between the non-hub nodes and hub-nodes are done by trucks only, (2) at most two IMTs may be used for freight flow through intermodal network, (3) IMTs have an inventory holding capacity. Figure 3.2 below shows how we represent a network for our modeling purpose.

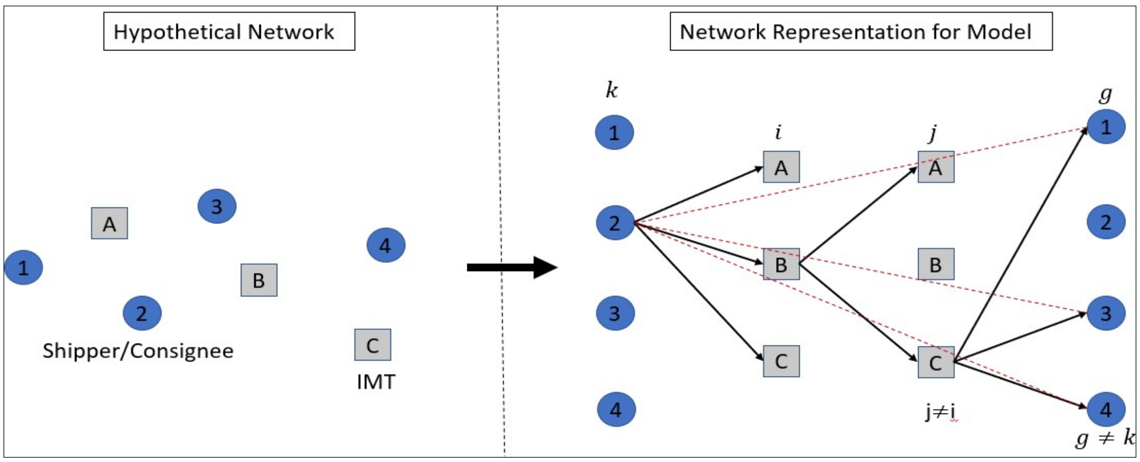

Figure 3.2: Network representation for model.

For every shipper/consignee (customer), the extreme left node represents the shipper aspect while the extreme right node represents the consignee aspect. So, we can't go from customer 2 to customer 2. The IMTs too have been represented in a way that we can't go from IMT B to IMT B.

In this study we propose a multiple-allocation capacitated mixed integer linear programming model. The model aims at: (1) locating the optimal number of intermodal terminals, (2) making allocating decisions, (3) making routing decisions, (4) making mode selection between IMTs, (5) deciding if to hold inventory at IMTs or not. The objective of the model is to minimize the total cost of the network (which includes the fixed cost of opening new IMTs, transportation costs, loading and unloading costs at IMTs and holding costs at the IMTs) throughout the planning horizon. The planning horizon is the entire time-period for which strategic planning is done and can further divided into shorter time periods of equal or unequal duration.

3.1.2 Mathematical formulation

Sets and parameters

N Set of all nodes
H Set of candidate hubs, $H \subset N$
P Set of Products
M Set of transportation modes
T Set of time periods

F_i fixed cost for locating an IMT at node $i \in H$
f_{ijm}^t fixed cost for using a terminal link using mode m between IMTs $i \in H$ and $j \in H$ for period $t \in T$
CI_{ijm}^t per unit transportation cost for product p from IMT $i \in H$ to IMT $j \in H$ using mode $m \in M$ for period $t \in T$
CP_{kpi}^t per unit drayage cost for product $p \in P$ from shipper $k \in N$ to IMT $i \in H$ using road transport for period $t \in T$
CE_{jgp}^t per unit drayage cost for product $p \in P$ from IMT $j \in H$ to receiver $g \in N$ using road transport for period $t \in T$
CU_{ip}^t per unit unloading cost for product $p \in P$ at IMT $i \in H$ for period $t \in T$
CL_{ip}^t per unit loading cost for product $p \in P$ at IMT $i \in H$ for period $t \in T$
CH_{ip}^t per unit holding cost for product $p \in P$ at IMT $i \in H$ for period $t \in T$
CD_{kgp}^t per unit direct shipping cost for product $p \in P$ between shipper $k \in N$ and receiver $g \in N$ for period $t \in T$
D_{gkp}^t demand for product $p \in P$ originating from shipper $k \in N$ at receiver $g \in N$ for period $t \in T$
DT_{gp}^t total demand for product $p \in P$ at receiver $g \in N$ for period $t \in T$
S_{kp}^t supply available at shipper $k \in N$ for period $t \in T$
V_p volume of product $p \in P$
V_m volume capacity of mode $m \in M$
V_t volume capacity of a truck
TI_{ijm}^t number of trips available between IMTs $i \in H$ and $j \in H$ for a mode $m \in M$ in period $t \in T$
TP_{ki}^t number of pre-haul trips available between shipper $k \in N$ and IMT $i \in H$ in period $t \in T$
TE_{jg}^t number of end-haul trips available between IMT $j \in H$ and receiver $g \in N$ in period $t \in T$
TD_{kg}^t number of direct shipping trips available between shipper $k \in N$ and receiver $g \in N$ in period $t \in T$
C_i material handling capacity of IMT $i \in H$ in period $t \in T$
HC_i holding capacity of IMT $i \in H$ in period $t \in T$
B budget for the entire planning horizon

Decision variables

$$F_i = \begin{cases} 1, & \text{if an IMT } i \in H \text{ is opened in period } t \in T \\ 0, & \text{otherwise} \end{cases}$$

$$f_{ijm}^t = \begin{cases} 1, & \text{if a terminal link between IMTs } i \in H \text{ and } j \in H \text{ is used in period } t \in T \\ 0, & \text{otherwise} \end{cases}$$

$$\xi_i = \begin{cases} 1, & \text{if IMT } i \in H \text{ is opened in period } t \in T \\ 0, & \text{otherwise} \end{cases}$$

q_{kip}^{t} number of units of product $p \in P$ shipped from supplier $k \in N$ to IMT $i \in H$ using direct shipping in period $t \in T$

r_{jgkp}^{t} number of units of product $p \in P$ originating from shipper $k \in N$ shipped from IMT $j \in H$ to customer $g \in N$ using road transport for period $t \in T$

w_{kgp}^{t} number of units of product $p \in P$ direct shipped from shipper $k \in N$ to receiver $g \in N$ in period $t \in T$

u_{ik}^{t} number of units of product $p \in P$ originating from shipper $k \in N$ unloaded at IMT $i \in H$ in period $t \in T$

I_{ik}^{t} number of units of product $p \in P$ originating from shipper $k \in N$ loaded at IMT $i \in H$ in period $t \in T$

h_{ik}^{t} number of units of commodity $p \in P$ originating from shipper $k \in N$ held by IMT $i \in H$ in period $t \in T$

Objective
Minimize

$$\sum_{i \epsilon H} F_i \xi_i + \sum_{i \epsilon H} \sum_{j \epsilon H} \sum_{m \epsilon M} \sum_{t \epsilon T} f_{ijm}^{t} z_{ijm}^{t} + \sum_{i \epsilon H} \sum_{j \epsilon H} \sum_{m \epsilon M} \sum_{k \epsilon N} \sum_{p \epsilon P} \sum_{t \epsilon T} CI_{ijmp}^{t} x_{ijmkp}^{t}$$
$$+ \sum_{k \epsilon N} \sum_{i \epsilon H} \sum_{p \epsilon P} \sum_{t \epsilon T} CP_{kip}^{t} q_{kip}^{t} + \sum_{j \epsilon H} \sum_{g \epsilon N} \sum_{k \epsilon N} \sum_{p \epsilon P} \sum_{t \epsilon T} CE_{jgp}^{t} r_{jgkp}^{t} + \sum_{i \epsilon H} \sum_{k \epsilon N} \sum_{p \epsilon P} \sum_{t \epsilon T} CU_{ip}^{t} u_{ikp}^{t} \quad (1)$$
$$+ \sum_{i \epsilon H} \sum_{k \epsilon N} \sum_{p \epsilon P} \sum_{t \epsilon T} CL_{ip}^{t} l_{ikp}^{t} + \sum_{i \epsilon H} \sum_{k \epsilon N} \sum_{p \epsilon P} \sum_{t \epsilon T} CH_{ip}^{t} h_{ikp}^{t} + \sum_{k \epsilon H} \sum_{g \epsilon N} \sum_{p \epsilon P} \sum_{t \epsilon T} CD_{kgp}^{t} h_{kgp}^{t}$$

Subject to

$$\sum_{\substack{j \in N, \\ j \neq i}} \sum_{m \in M} x_{jimkp}^{t} + \sum_{k \in N} q_{kip}^{t} + l_{ikp}^{t} = \sum_{m \in M} \sum_{j \in H} x_{ijmkp}^{t} + \sum_{\substack{j \in H, \\ j \neq i}} \sum_{g \in N} r_{jgkp}^{t} + u_{ikp}^{t} \quad \forall i \in H, k \in N, p \in P, t \in T \quad (2)$$

$$h_{ikp}^{t} = h_{ikp}^{t-1} + u_{ikp}^{t} - l_{ikp}^{t} \quad \forall i \in H, k \in N, p \in P, t \in T \quad (3)$$

$$w_{kgp}^{t} + \sum_{j \in H} r_{jgkp}^{t} \geq D_{gkp}^{t} \quad \forall g, k \in N: g \neq k, p \in P, t \in T \quad (4)$$

$$\sum_{k \in N} w_{kgp}^{t} + \sum_{k \in N} \sum_{j \in H} r_{jgkp}^{t} \geq DT_{gp}^{t} \quad \forall g \in N, p \in P, t \in T \quad (5)$$

$$\sum_{i \in H} q_{kip}^{t} + \sum_{\substack{g \in N, \\ g \neq k}} w_{kgp}^{t} \leq S_{kp}^{t} \quad \forall k \in N, p \in P, t \in T \quad (6)$$

$$\sum_{k\in N}\sum_{p\in P} x_{ijmkp}^{t} VP_p \le TI_{ijm}^{t} V_m z_{ijm}^{t} \quad \forall i,j\in H: i\neq j, m\in M, t\in T \tag{7}$$

$$\sum_{p\in P} q_{kip}^{t} VP_p \le TP_{ki}^{t} V_t y_i^{t} \quad \forall k\in N, i\in H, t\in T \tag{8}$$

$$\sum_{k\in N}\sum_{p\in P} r_{jgkp}^{t} VP_p \le TE_{jg}^{t} V_t y_j^{t} \quad \forall g\in N, j\in H, t\in T \tag{9}$$

$$\sum_{p\in P} w_{kgp}^{t} VP_p \le TD_{kg}^{t} V_t \quad \forall g\in N, j\in H, t\in T \tag{10}$$

$$\sum_{\substack{j\in H,\\ j\neq i}}\sum_{m\in M}\sum_{k\in N}\sum_{p\in P} x_{ijmkp}^{t} + \sum_{\substack{j\in H,\\ j\neq i}}\sum_{m\in M}\sum_{k\in N}\sum_{p\in P} x_{jimkp}^{t} \le C_i^{t} \quad \forall i\in H, t\in T \tag{11}$$

$$\sum_{i\in H} F_i \xi_i \le B \tag{12}$$

$$\sum_{k\in N}\sum_{p\in P} h_{ikp}^{t} \le HC_i^{t} \quad \forall i\in H, t\in T \tag{13}$$

$$z_{ijm}^{t} \le y_i^{t} \quad \forall i,j\in H: i\neq j, m\in M, t\in T \tag{14}$$

$$z_{ijm}^{t} \le y_j^{t} \quad \forall i,j\in H: i\neq j, m\in M, t\in T \tag{15}$$

$$y_i^{t} \ge y_i^{t-1} \quad \forall i\in H \tag{16}$$

$$M\xi_i \ge \sum_{t\in T} y_i^{t} \quad \forall i\in H \tag{17}$$

$$\begin{gathered} z_{ijm}^{t}, y_i^{t}, \xi_i \in \{0,1\} \quad \forall i,j\in H: i\neq j, m\in M, t\in T \\ q_{kip}^{t}, x_{ijmkp}^{t}, r_{jgkp}^{t}, w_{kgp}^{t}, u_{ik}^{t}, l_{ik}^{t}, h_{ik}^{t} \ge 0 \text{ and } Int \\ \forall k,g\in N: k\neq g, i,j\in H: i\neq j, m\in M, p\in P, t\in T \end{gathered} \tag{18}$$

The objective function (1) minimizes the total relevant network cost which includes the fixed cost of opening an IMT, fixed cost for using an intermodal link, cost of shipping between IMTs, cost of pre-hauls, cost of end-hauls, unloading cost, loading cost, holding cost at IMTs, and cost of direct shipping. Constraint (2) is flow balance constraint at IMTs and keeps track of number of loaded and unloaded units. Constraint (3) is the multi-period inventory constraint and makes sure that inventory at an IMT in a period is equal to the sum of inventory of preceding period and net units loaded or unloaded. Constraint (4) ensures that a consignee meets its demand of a specific freight type and specific supplier either intermodally or via direct shipping. Constraint (5) ensures that a consignee meets its net demand (specific and free demand). Constraint (6) ensures that a supplier can't ship more than available freight. Constraints (7-10) ensure that a mode does not ship freight volume more than net available volume. Constraint (11) is the throughput constraint at an IMT and considers both the inbound and outbound flows. Constraint (12) ensures that the budget to open intermodal terminals is not exceeded. Constraint (13) ensures that and IMT does not hold inventory more than its storage capacity. Constraints (14, 15) ensures that we use an intermodal link only if the IMTs connected by the link are open. Constraint (16) ensures that an IMT stays open for the succeeding periods once opened. Constraint (17) that we incur only a one-time fixed cost for opening an IMT. Constraint (18) is the variable type constraint.

3.2 Carrier collaboration problem

3.2.1 Problem definition

Carriers receive pickup and delivery jobs (referred as jobs from hereafter) from shippers. In carrier collaboration, several carriers form an alliance by sharing their jobs. Some carriers prefer to retain certain jobs to serve by their vehicles. Therefore, the jobs are either retained or they are released to a common pool for allocation among partners in the collaborative alliance by the central planner. Figure 3.3 shows how the retention, release, and reallocation of jobs happen in a LTLCC alliance having two carriers.

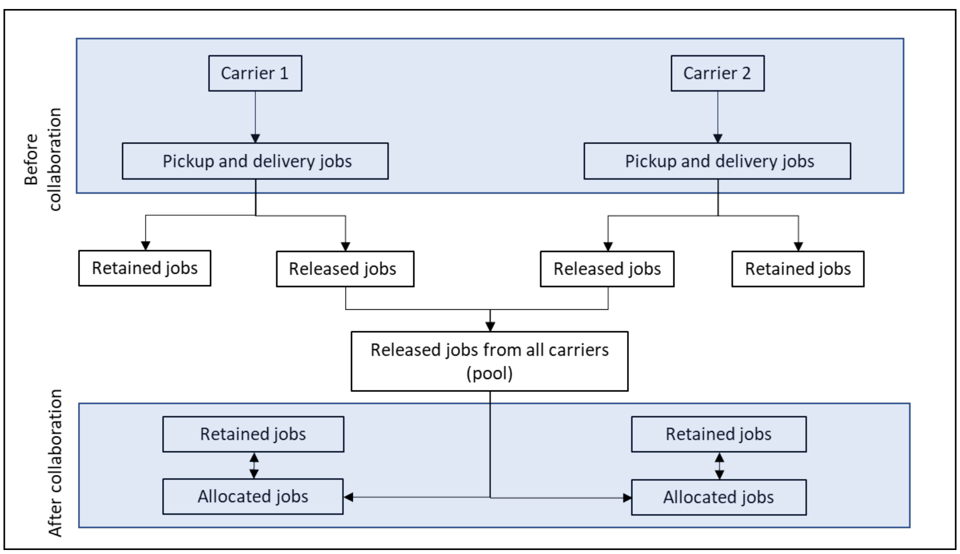

Figure 3.3: LTLCC problem having two carriers in the alliance.

The carrier collaboration problem is framed as, F number of carriers form a collaborative alliance and each carrier in the alliance is assumed to have their own depot. The set of all carrier depots in the alliance is denoted as $D = \{1, . . ., d\}$. Where d is the number of depots which is equal to the number of carriers F. Each carrier depot has $|V_f|$ number of vehicles, where f is the depot, $f = 1, . . ., d$ and V_f is the set of vehicles at depot f. It is assumed that the vehicles start and end each route at its own carrier depot. It is also assumed that $|V_f|$ is large enough to serve all jobs received by the carrier of depot *f*. If *n* is the total number of jobs received by all carriers in the alliance, job *l*, *l =1, . . ., n* consists a pickup node *l + d* and a corresponding delivery node *l + d + n*. Set of pickup nodes of all jobs received by all carriers in the collaborative alliance are represented as *PK* = {*d + 1, . . ., n + d*} and set of delivery nodes are represented as *DL* = {*n + d + 1, . . ., 2n + d*}. Union of sets *PK* and *DL* is represented as set *O* which represents all customer-nodes in the network. The union of sets *D* and *O* is denoted as *N* which represents the set of all nodes in the network.

All nodes in the network are located on a 2-D plane and the cost for a vehicle to traverse the arc connecting $i \in N$ and $j \in N$ is C_{ij}. In this problem, the cost between two nodes is proportional to the distance between the nodes. The quantity of freight to pick up or delivery at node $i \in O$ is denoted q_i. If q_i is positive, the required service is a pickup and if it is negative, the service is a delivery. It is assumed that all vehicles in the alliance, denoted as set *V* have same capacity with *K*. Maximum hour that vehicles travel is restricted with an upper limit of *H* and this limit is imposed on all vehicle routes. Each customer, located at and represented by node $i \in O$, has a time window for service, [a_i, b_i]. The time at which the vehicle $v \in V$ starts servicing node $i \in N$ is S_i^v and the time required to travel from node $i \in N$ to node $j \in N$ is T_{ij}. The time S_i^v is calculated only if the node *i* is visited by vehicle *v*.

The proposed mathematical model minimizes the total transportation cost in such a way that all jobs are served within their time windows, vehicle capacity is never exceeded, and each vehicle starts and ends its trip at its own carrier depot. The model allow each carrier to retain certain jobs, optimally allocates all jobs in the released job pool and develops optimal vehicle routes that ensures all jobs are served and that no restriction on maximum hour traveled in a single vehicle route is violated.

3.2.2 Mathematical formulation

Sets

D = {*1, . . ., d*}, set of depots
PK = {*d + 1, . . ., n + d*}, set of pickup nodes
DL = {*n + d + 1, . . ., 2n + d*}, set of delivery nodes
$O = PK \cup DL$, set of all pickup and delivery nodes
$N = D \cup O$, set of all nodes
$V_f = \{1, . . ., v_f\}$, set of vehicles at depot *f* where *f = 1, . . ., d*
$V = V_1 \cup V_2 \cup .... \cup V_f$, set of all vehicles
R_f = Set of pickup and delivery nodes of retained jobs of carrier corresponding to depot *f*, where *f = 1, . . ., d*

Parameters

F = Number of carriers in the collaborative alliance
K = Vehicle capacity
H = Maximum hour allowed in one vehicle route
C_{ij} = Cost of travel from node $i \in N$ to node $j \in N$
q_i = Demand/supply at node $i \in O$ (positive sign represents a pickup and negative sign represents a drop off)
T_{ij} = Time required to traverse the arc connecting node $i \in N$ and node $j \in N$
a_i = The earliest acceptable pickup/ delivery time at node $i \in O$

b_i = The latest acceptable pickup/ delivery time at node $i \in O$
M = Large number
p = Total number of jobs

Decision variables

$$x_{ij}^{\ v} = \begin{cases} 1 \text{ if vehicle } v \in V \text{ traverses the arc connecting } i \in N \text{ and } j \in N \\ 0 \text{ otherwise} \end{cases}$$

Q_{ij}^v = Quantity transported across arc ($i \in N, j \in N$) by vehicle $v \in V$

S_i^v = The time at which the vehicle $v \in V$ begins the service at node $i \in N$

Objective

Minimize,

$$Z = \sum_{v\in V}\sum_{i\in N}\sum_{j\in N} C_{ij} x_{ij}^{\ v} \tag{19}$$

Subject to,

$$\sum_{j\in N} x_{ji}^{\ v} - \sum_{j\in N} x_{ij}^{\ v} = 0, \quad \forall \quad i \in N, v \in V \tag{20}$$

$$Q_{ij}^v \le K x_{ij}^v, \quad \forall \quad i \in N, j \in N, v \in V \tag{21}$$

$$\sum_{v\in V}\sum_{j\in O, i\ne j} Q_{ij}^{\ v} - \sum_{v\in V}\sum_{j\in O, i\ne j} Q_{ji}^{\ v} = q_i, \quad \forall \quad i \in O \tag{22}$$

$$\sum_{i\in N}\sum_{j\in N} T_{ij} x_{ij}^{\ v} \le H, \quad \forall \quad \text{v} \in V \tag{23}$$

$$x_{ij}^{\ v} = 0, \quad \forall \quad i \in D, j \in D, v \in V \tag{24}$$

$$\sum_{v\in V}\sum_{i\in N} x_{ij}^v \le 1, \quad \forall \quad j \in O \tag{25}$$

$$\sum_{v\in V, v\notin V_f} x_{ij}^{\ v} = 0, \quad \forall \quad f \in D, i \in N, j \in R_f \tag{26}$$

$$S_j^{\ v} \ge S_i^{\ v} + T_{ij} x_{ij}^{\ v} - M(1 - x_{ij}^{\ v}), \quad \forall \quad i \in N, j \in O, v \in V, i \ne j \tag{27}$$

$$a_i \le S_i^v \le b_i, \quad \forall \ i \in O, \ \text{v} \in V \tag{28}$$

$$\sum_{v\in V, v\notin V_i}\sum_{j\in O} x_{ij}^v = 0, \quad \forall \quad i \in D \tag{29}$$

$$\sum_{j\in N} x_{ij}^{\ v} \le 1, \forall i \in D, v \in V \tag{30}$$

$$S_i^{\ v} \le S_{i+p}^{\ \ v}, \quad \forall \quad i \in PK, v \in V, i \ne j \tag{31}$$

$$\sum_{j\in O} x_{ij}^{\ v} - \sum_{j\in N} x_{i+nj}^{\ \ v} = 0, \quad \forall \quad i \in PK, v \in V \tag{32)+ $$

$$Q_{ij}^{\ vp} \ge 0, \quad \forall \quad \text{v} \in V, i \in N, j \in N, p \in P \tag{33}$$

$$S_i^v \ge 0, \quad \forall i \in N, v \in V \tag{34}$$

The objective function (19) minimizes the total cost of transportation in the collaborative alliance. Constraints (20) ensure that a vehicle arriving at a node must leave the node. Constraints (21) are the vehicle capacity constraints. Constraints (22) are flow balance across each node. They guarantee that the difference between the incoming and the outgoing products flow in a node will equal the supply or demand at that node. Constraints (23) restrict the maximum hour traveled in one vehicle route. Constraints (24) prohibit vehicles from traveling from one depot to another depot. Constraints (25) ensure that no customer/node is visited more than once. Constraints (26) ensure that the vehicles of a carrier will not serve the retained jobs of other carriers. Constraints (27) and (28) force the vehicles to operate within the time window constraints. Constraints (27) gives the time (S_j^v) at which the vehicle v start from $j \in N$, if the vehicle v is going from node i to node j. A big number M makes the right-hand side negative if the arc (i, j) is not active (i.e., $x_{ij}^v=0$) which ensures that the constraint (27) is only applicable for active arcs. The constraints (27) also ensure that the vehicles start and end only at the carrier depots and thus eliminates subtour formation. Constraints (28) ensure that the time at which a vehicle starts from a node $i \in N$ is within the allowable time window; i.e., greater than the earliest pickup/ delivery time and less than the latest pickup/ delivery time of that node. Constraints (29) ensure that the vehicles must start and end at their own carrier depots. Constraints (30) ensure that a vehicle must not originate from a depot more than once. Constraints (31) ensure that the pickup node is visited before the corresponding delivery node. Constraints (32) guarantee that both pickup and delivery of a job is served by the same vehicle. (33) and (34) are the non- negativity constraints.

CHAPTER 4
Results and Discussion

4.1 Intermodal terminal location problem

4.1.1 Significant factors

A hypothetical network consisting of 25 nodes was developed with 20 customers (shippers/consignees) nodes and 5 candidate intermodal hub nodes. Five different product types (w.r.t. product volume) are considered in this network. The modes considered between the intermodal terminals for this example are: (1) Rail, (2) Two 53 ft-trailer truck, and (3) 40 ft-trailer truck which have different volume constraints on the freight capacity. The data for the model was randomly generated using the knowledge from literature review and is shown below in table 4.1.

Table 4.1: Data used for the parameters

Parameter	Range/Value				
IMT material handling capacity (units)	rand (30,000-40,000)				
IMT material holding capacity (units)	rand (500-600)				
Product Volume (cubic m)	**Product 1**	**Product 2**	**Product 3**	**Product 4**	**Product 5**
	1	2	3	4	5
Transportation cost ($ per mile/unit)	**Rail**				
	Product 1	**Product 2**	**Product 3**	**Product 4**	**Product 5**
	rand (0.10-0.30)	rand (0.30-0.50)	rand (0.50-0.60)	rand (0.80-0.90)	rand (0.90-1.00)
	Two 53 ft-trailer truck				
	Product 1	**Product 2**	**Product 3**	**Product 4**	**Product 5**
	rand (0.50-0.70)	rand (0.70-0.90)	rand (0.90-1.10)	rand (1.10-1.30)	rand (1.30-1.50)
	40 ft-trailer truck				
	Product 1	**Product 2**	**Product 3**	**Product 4**	**Product 5**
	rand (3.50-4.00)	rand (4.00-4.50)	rand (4.50-5.00)	rand (5.00-5.50)	rand (5.50-6.00)
Number of Pre-haul trips	rand (70-90)				
Number of End-haul trips	rand (70-90)				
Number of Intermodal trips	**Rail**	**Two 53 ft-trailer truck**		**40 ft-trailer truck**	
	rand (0-2)	rand (10-20)		rand (10-25)	
Loading costs ($ per unit)	**Product 1**	**Product 2**	**Product 3**	**Product 4**	**Product 5**

	rand (25-30)	rand (30-35)	rand (35-40)	rand (40-45)	rand (45-50)
Unloading costs ($ per unit)	**Product 1**	**Product 2**	**Product 3**	**Product 4**	**Product 5**
	rand (20-25)	rand (25-30)	rand (30-35)	rand (35-40)	rand (40-45)
Direct Shipping costs ($ per mile/unit)	**Product 1**	**Product 2**	**Product 3**	**Product 4**	**Product 5**
	rand (3.50-4.00)	rand (4.00-4.50)	rand (4.50-5.00)	rand (5.00-5.50)	rand (5.50-6.00)
Fixed cost of opening an IMT ($)	rand (12000-15000)				
Fixed cost for operating a mode between IMTs ($)	**Rail**	**Two 53 ft-trailer truck**		**40 ft-trailer truck**	
	rand (100-200)	rand (80-100)		rand (50-60)	

Since, there are many factors involved, a 2^4 Full Factorial Design was performed to do the screening for significant factors for total network cost and intermodal shipping volumes. The outputs considered for the experiments are: (1) Intermodal Shipping Volume, and (2) Total Network Cost. The inputs considered for screening are: (1) Product Volume, (2) Mode Volume, (3) Holding Capacity, and (4) Budget. The high level and low level settings selected for the inputs are shown in table 4.2.

Table 4.2: A 2^4 full factorial design for significant factor screening

Factors	High level (+)					Low level (-)				
Product Volume (cubic m) **(A)**	**P1**	**P2**	**P3**	**P4**	**P5**	**P1**	**P2**	**P3**	**P4**	**P5**
	3	5	7	9	11	1	2	3	4	5
Mode Volume (cubic m) **(B)**	**Rail**	**Two 53 ft-trailer truck**		**40 ft-trailer truck**		**Rail**	**Two 53 ft-trailer truck**		**40 ft-trailer truck**	
	2000	400		120		1000	200		60	
Holding Capacity (cubic m) **(C)**	**t=1**	**t=2**	**t=3**	**t=4**		**t=1**	**t=2**	**t=3**	**t=4**	
	rand (1500-1650)	rand (900-1000)	rand (750-800)	rand (450-550)		rand (100-150)	rand (100-150)	rand (100-150)	rand (100-150)	
Budget ($) **(D)**	60,000					30,000				

For the FFD, interactions higher than 2nd order were not considered. For both the outputs the inputs considered were same. The model was solved using the Gurobi solver and the FFD was carried out in Maple. The normal plots obtained for the Intermodal

Shipping Volume and Total Network Cost are shown in Figure 4.1 and Figure 4.2. Based on the FFD the factors identified as significant are shown in table 4.3.

Table 4.3: Significant factors for the respective outputs

Intermodal Shipping Volume	Total Network Cost
Budget (D)	Product Volume (A)
Mode Volume (B)	Mode Volume (B)
Holding Capacity (C)	Budget (D)
Product Volume (A)	Product Volume-Mode Volume (AB)
Budget-Mode Volume (BD)	Mode Volume-Budget (BD)
	Product Volume-Budget (AD)

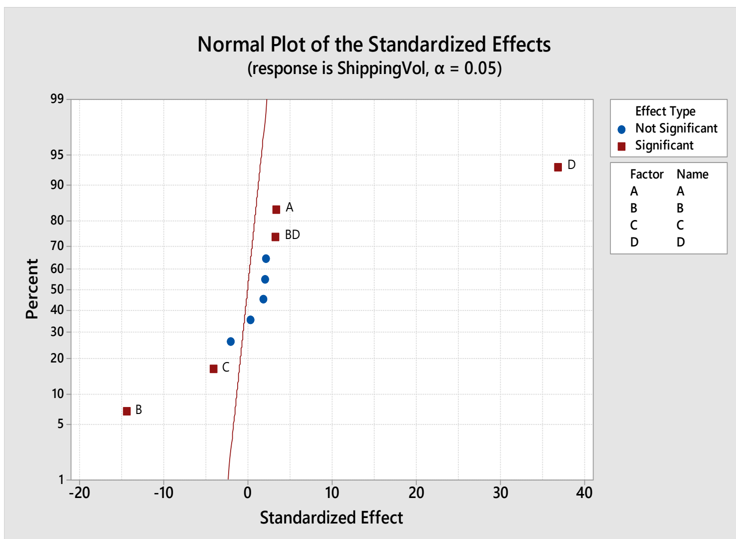

Figure 4.1: Normal plot for intermodal shipping volumes

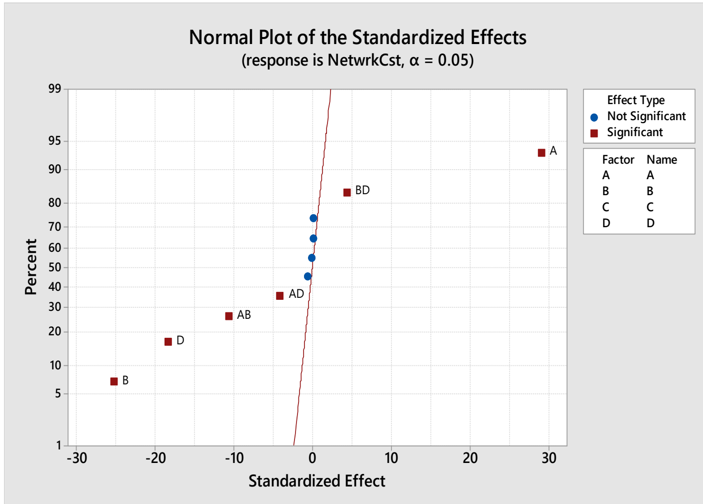

Figure 4.2: Normal plot for total network cost

4.1.2 Computation results for the hypothetical network

The effect of significant factors on the intermodal shipping volumes and total network cost was analyzed by designing a set of experiments which are discussed below.

Holding Capacity of Intermodal Terminals

The Intermodal terminals' holding capacity was varied for all the IMTs from low to high (same for all the time periods) to identify its impact on the total network cost, intermodal shipping volumes and utilization of modes with different capacities.

It is evident from table 4.4 that the total network cost decreases when the holding capacity is increased as the network has more flexibility. When there is no holding capacity at the IMTs the model chooses the mode with lowest transportation cost available for that time-period and increases the cheaper mode's utilization (i.e. rail). Whereas the holding capacity in a network can meet the demands for succeeding time periods by pushing the freight to the IMTs in time periods of lower transportation costs, holding freight there and then moving freight using the cheapest option available at the right destination and the right time-period.

Table 4.4: Impact of holding capacity on respective variables

Holding Capacity (units)	T. Network Cost ($)	Intermodal Shipping Share (%)	Rail Utilz. (%)	Two-53 ft. trailer truck Utilz. (%)	40 ft. trailer truck Utiliz. (%)
0	191,037,567	59.65	15.19	14.09	1.34
100	189,810,114	59.16	15.16	14.07	0.83
200	189,361,730	59.1	15.16	13.96	1.04
300	189,206,371	58.72	15.16	14	0.73
400	189,130,419	59.16	15.16	14.07	0.73

500	189,070,800	59.6	15.16	14.21	0.73
100000	189,009,585	60	15.16	14.42	0.73

The flexibility gained by the network depends on the holding capacity and the mode availability. When at low holding capacities, model uses the cheapest mode although it is less frequent, but at high holding capacities, model analyses the tradeoff between transportation cost and availability of a mode for a time-period. Therefore, as observed in Table 4.4 and Figure 4.3, the utilization of the cheapest mode, Rail is highest at no holding but as we increase the holding capacity utilization of slightly costlier but more available mode, Two-53 ft. trailer truck starts increasing.

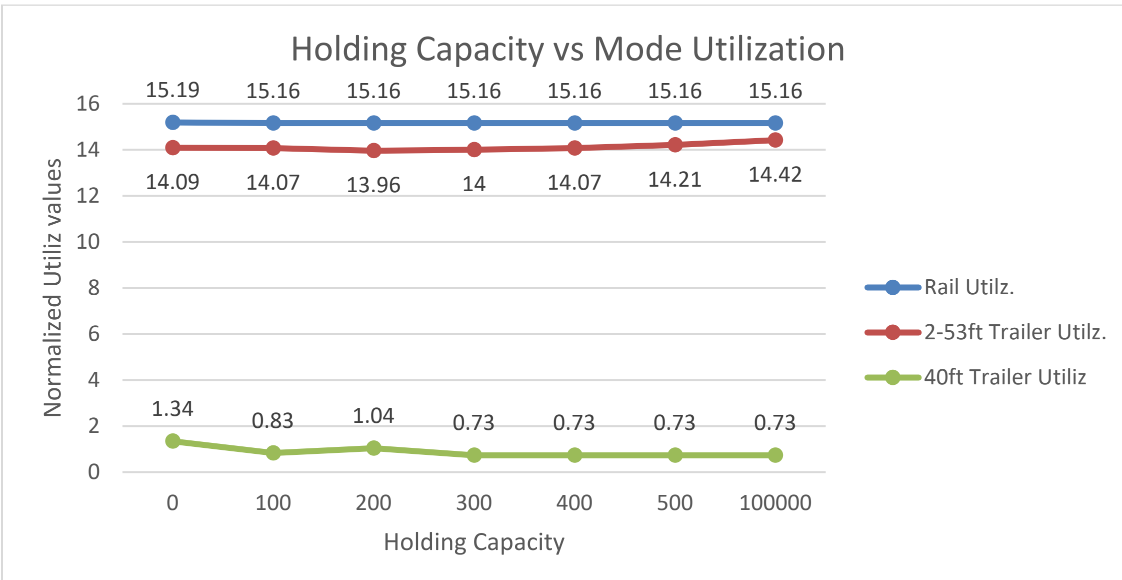

Figure 4.3: Mode utilizations for the available modes between IMTs

<u>Product Volume</u>

The network performance was evaluated for three different scenarios: (1) low volume products, (2) medium volume products, and (3) high volume products in the network. The study validates the fact that total network cost increases as the product volume in the network increases. We also observe that utilizations of the low transportation cost and high capacity modes increases with increase in product volumes. Figure 4.4 shows a sudden increase in the utilization of 2-53 ft. trailer truck when product volume increases as it has more availability and low transportation cost per unit, whereas the lowest transportation cost mode (i.e. Rail) has a low availability.

Table 4.5: Impact of product volume on respective variables

Product Volume (P1, P2, P3, P4, P5) (cubic m)	T. Network Cost ($)	Intermodal Shipping Share (%)	Rail Utilz. (%)	Two-53 ft. trailer truck Utilz. (%)	40 ft. trailer truck Utiliz. (%)	IMT Holding Capacity Utilz. (%)
Low (1, 2, 2.5, 3, 3.5)	185,010,852	59.16	14.8	12.6	0.94	10.65

Medium (2, 3, 4, 5, 6)	206,642,879	56.27	15.88	18.91	0.61	14.5
High (2.5, 3.5, 4.5, 5.5, 6.5)	214,738,065	54.98	16.11	19.79	0.61	15.09

The intermodal shipping share decreases by approx. 4.2% when product volume changes from low to high as the required mode capacity increases for higher volume products, therefore depending on the mode availability freight in the network can be shared with the direct shipping modes.

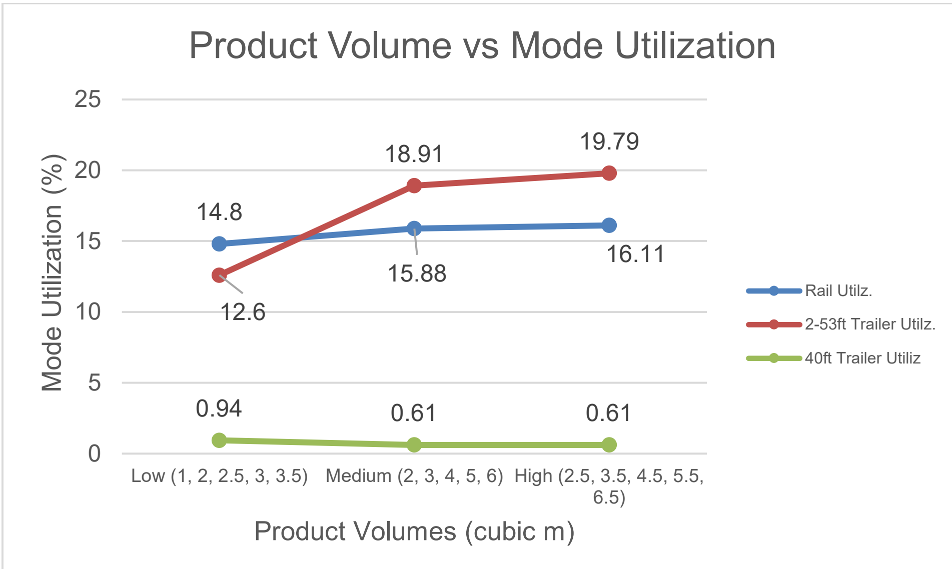

Figure 4.4: Effect of product volume on mode utilizations

IMTs can reduce the network cost in scenarios of higher transportation capacity demand (i.e. higher product volume). Model moves the freight demand for succeeding time-periods when it has unused lower transportation cost capacity available and holds it for a few periods to dispatch it at the required moment. This can be seen in Table 4.5 and Figure 4.5, as product volume increases, the IMTs' holding capacity utilization increases by approx. 4.5%.

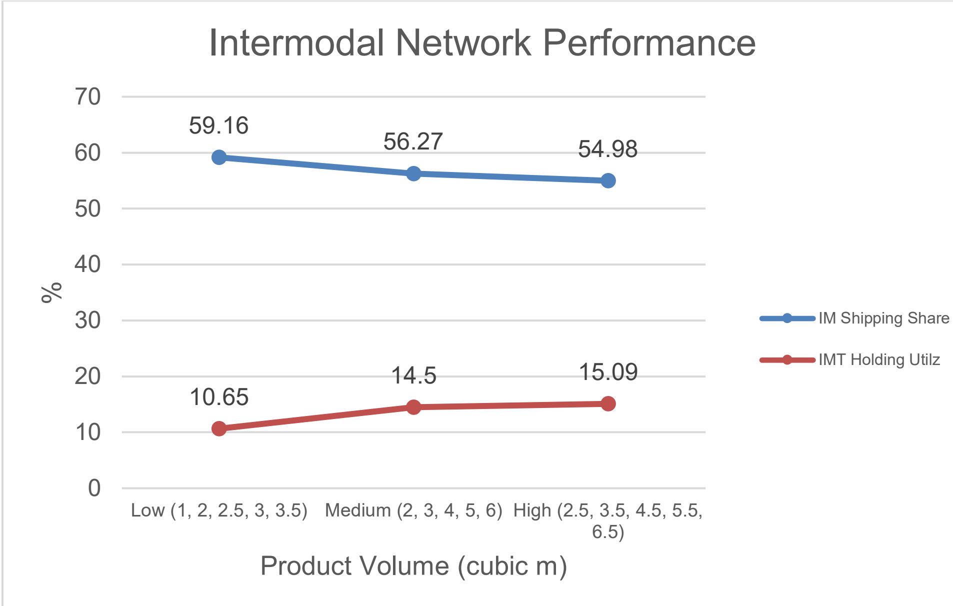

Figure 4.5: Effect of product volume on Intermodal shipping share and IMTs' holding capacity utilization

Budget

The budget for the entire planning horizon greatly impacts the intermodal shipping. The more budget available the more IMTs we can open and more intermodal links we can access. For the hypothetical example increasing the budget slightly decreases the total network cost up to 10%, as we can open more IMTs, use the available lower transportation cost modes and the holding capacity at the IMTs. Table 4.6 shows very clearly that on increasing the budget slightly the intermodal shipping share increases, mode utilization of the lowest transportation cost mode, Rail increases and the holding capacity utilization of the IMTs increases.

Table 4.6: Impact of budget on respective variables

Budget ($)	T. Network Cost ($)	Intermodal Shipping Share (%)	Rail Utilz. (%)	Two-53 ft. trailer truck Utilz. (%)	40 ft. trailer truck Utiliz. (%)	IMT Holding Capacity Utilz. (%)
30000	210,420,952	44.53	4.31	6.58	1.49	10.74
40000	189,067,941	59.62	15.16	14.22	0.73	12.43
50000	185,781,773	60.62	23.32	13.25	0	15.01
60000	175,523,380	67.92	40.45	12.81	0	29.99
70000	167,372,099	74.89	51.53	13.24	0	37.28
1000000	167,372,099	74.89	51.53	13.24	0	37.28

Mode Volume

The mode volumes represent the freight volume transportation capacity of a mode, and we test the model for three different scenarios with different mode volumes: (1) Low, (2) Medium, and (3) High.

As the mode volume increases the network cost decreases as the freight can be handled using lesser mode capacity or lesser number of trips. The intermodal shipping shares also increases as we can carry more freight in a mode at an IMT for the same availability. Table 4.7 shows that as the mode volume increases, number of units shipped by the lowest transportation cost and highest capacity mode increases (i.e. Rail).

Table 4.7: Impact of mode volume on respective variables

Mode Volume (M1, M2, M3) (cubic m)	T. Network Cost ($)	Intermodal Shipping Share (%)	Rail Shipping (Units)	Two-53 ft. trailer truck Shipp. (Units)	40 ft. trailer truck Shipp. (Units)
Low (500, 50, 30)	198,114,283	54.45	6008	8450	1293
Medium (1000, 100, 60)	189,067,941	59.62	11048	11101	360
High (2000, 200, 120)	184,568,082	62.05	16512	9314	0

Types of Modes

The model was tested by changing the type of modes available between the IMTs as shown in table 4.8.

Table 4.8: Impact of different type of modes available between IMTs

Type of Mode between IMTs	T. Network Cost ($)	Intermodal Shipping Share (%)	Rail Utilz. (%)	Two-53 ft. trailer truck Utilz. (%)	40 ft. trailer truck Utiliz. (%)	IMT Holding Capacity Utilz. (%)
Rail	204,950,196	48.85	15.57	N/A	N/A	14
2-53ft Trailer	197,630,365	55.65	N/A	18.8	N/A	12.73
40 ft Trailer	218,909,492	47.46	N/A	N/A	12.6	15.81
Rail and 2-53ft Trailer	189,165,844	59.62	15.16	14.22	N/A	12.44
Rail and 40ft Trailer	201,675,256	50.43	15.58	N/A	6.03	11.56
2-53ft Trailer and 40ft Trailer	197,015,520	56.24	N/A	18.97	2.48	10.61
All three modes	189,067,941	59.62	15.16	14.22	0.73	12.44
No Mode	226,890,321	41.08	N/A	N/A	N/A	12.69

It is observed that the best performing case was when we used all the three modes, which offered us both low transportation costs and availability of modes. The second best performing case was for Rail and Two-53 ft. trailer truck as it had low transportation costs and high availability. As depicted in Figure 4.6, two-53 ft. trailer truck performed better alone and in combination with other modes than Rail despite having higher transportation costs as it had higher available capacity for the freight movement.

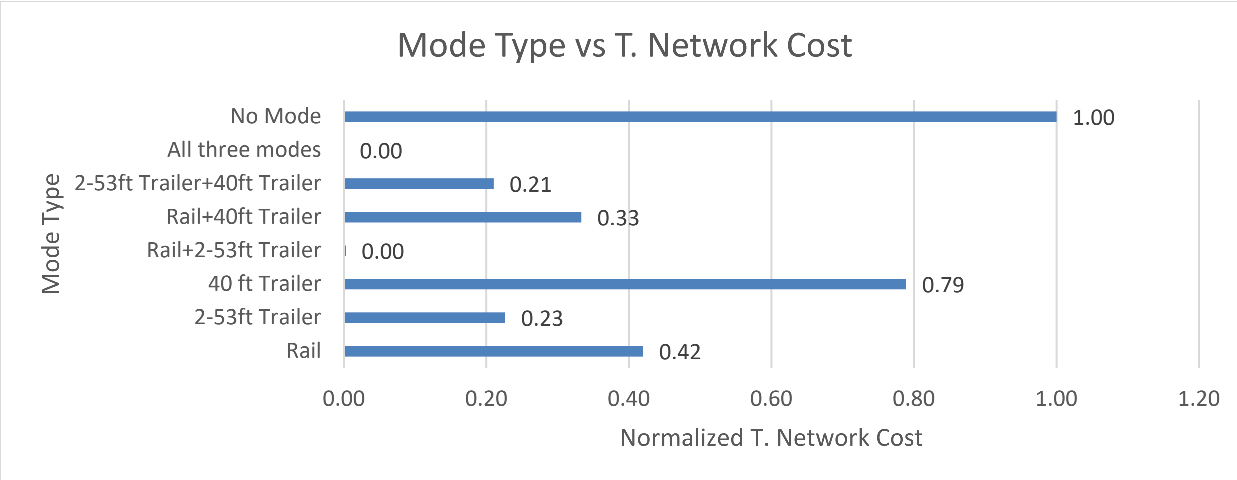

Figure 4.6: Impact of available intermodal mode type on total network cost

Figure 4.7 shows that the IMT holding utilization was highest when only 40 ft. trailer truck was available between the IMTs as it had the highest availability among all the modes available, thus offered the network highest flexibility.

The intermodal shipping share was highest for the scenario when all the three modes were available as again it offered lowest transportation costs and highest availability.

When no mode is available between IMTs, the model uses freight flow through single IMTs to use the consolidation and freight holding at IMTs for the freight destined to consignees in proximity.

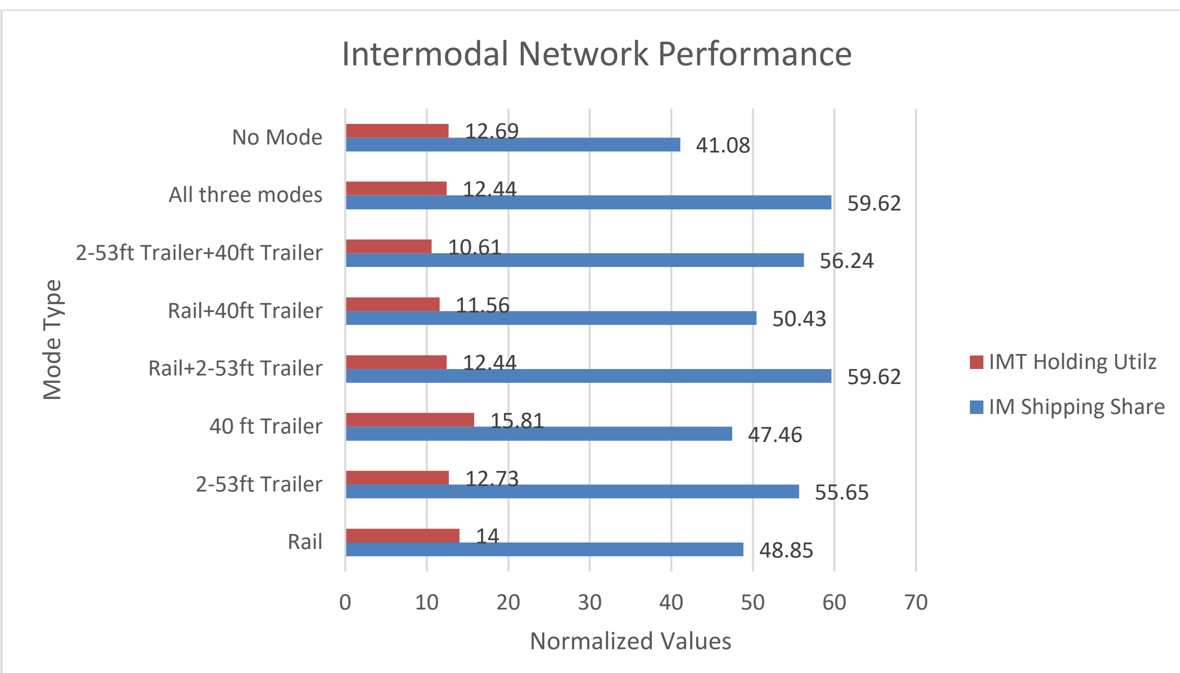

Figure 4.7: Impact of mode type on intermodal shipping share and IMT holding utilization

4.2 Carrier collaboration problem

Experiments are conducted on various hypothetical networks. These networks are generated by randomly locating nodes on a 2D-plane and the cost between any two nodes are estimated as proportional to the distance between them. The travel time between two nodes is calculated by dividing the distance between the nodes by the average truck velocity (55mph). All networks consist of 2 carriers (one depot for each carrier) and the jobs received by them. For example, an 18-node network is shown in Figure 4.8. In Figure 4.8, the two nodes that are connected by a line represents one pickup and delivery job pair and the arrow directs towards delivery. The details of pickup and delivery jobs for the 18-node network are shown in table 4.9.

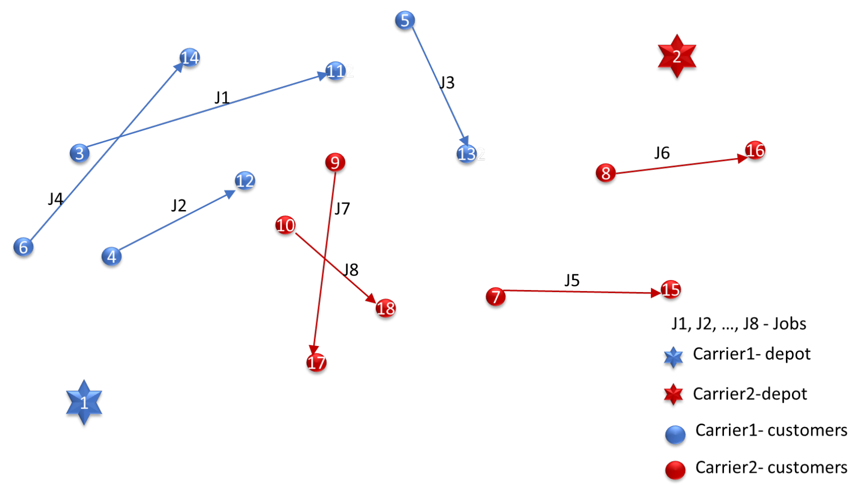

Figure 4.8: Pickup and delivery jobs received by carrier 1 and carrier 2 for an 18-node network

Table 4.9: Pickup locations, delivery locations, time windows and shipment details of jobs

Job	1	2	3	4	5	6	7	8
Pickup node	3	4	5	6	7	8	9	10
Delivery node	11	12	13	14	15	16	17	18
Pickup time window	[50, 73]	[26, 53]	[48, 52]	[33, 87]	[27, 50]	[23, 55]	[38, 51]	[28, 89]
Delivery time window	[53, 84]	[35, 93]	[54, 59]	[41, 90]	[42, 92]	[51, 81]	[56, 86]	[59, 75]
Quantity	50	50	50	50	50	50	50	50

It should be noted that this problem belongs to the class of Nondeterministic Polynomial-time Complete (NPC) problems because it is an extension of the vehicle routing problem which has been shown to belong to the class of NPC problems. This means that all known algorithms that define an optimal solution require exponentially increasing computational time as the number of markers and stencils increase. Therefore, large neighborhood search heuristic is used to solve the bigger network. The mathematical model is solved using Gurobi solver for small networks such as 18, 20, and 22 nodes networks.

The 18-node network is solved in Gurobi solver using the data shown in table 4.9 and the vehicle capacity of 100 units. The results show that, after collaboration, carrier 1 serves its retained jobs (job 1 and 2), one of the jobs it released (job 4) and two of the released jobs of carrier 2 (job 7 and 8). Carrier 2 serves its retained jobs (jobs 5 and 6) and one of the released jobs of carrier 1 (job 3). The minimum cost route that each carrier would have traveled without collaboration is shown in Figure 4.9. This is obtained by solving the pickup and delivery problem for each carrier separately by considering only the jobs received by their own. The routes after collaboration for the same network are shown in Figure 4.10. The retained jobs are also highlighted in this network. In Figures 4.9 and 4.10, the values near each arc in brackets shows the arc flow-quantity and the value in square bracket near every node represents the demand or supply of that node.

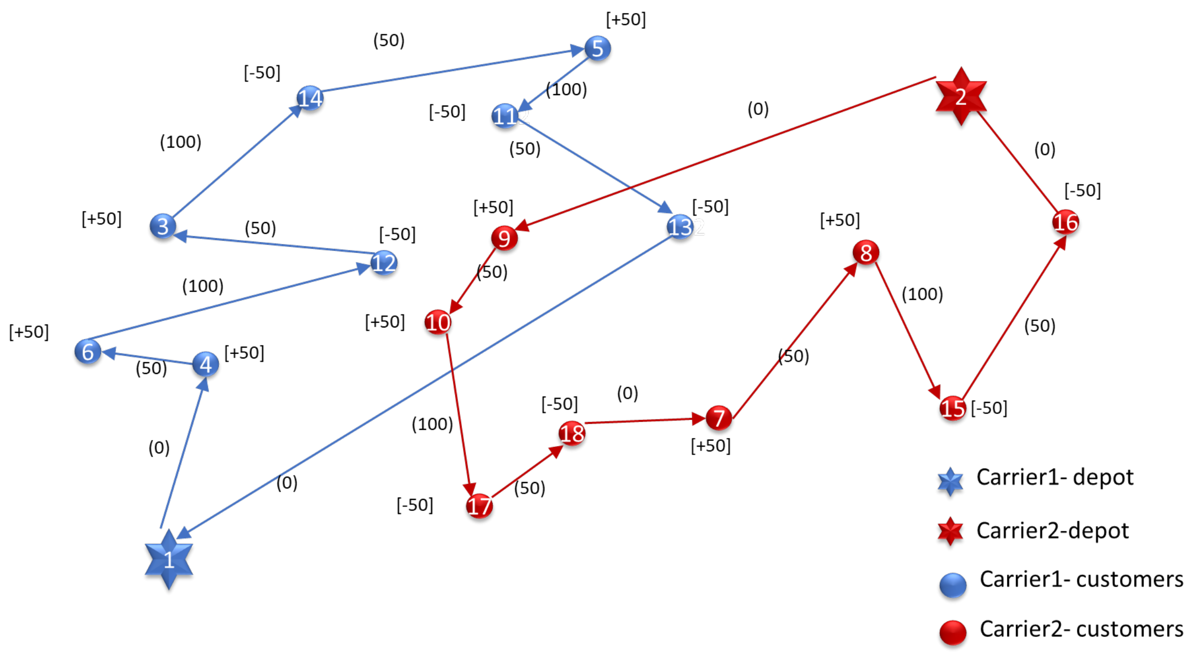

Figure 4.9: Vehicle route of the illustrative example – without collaboration

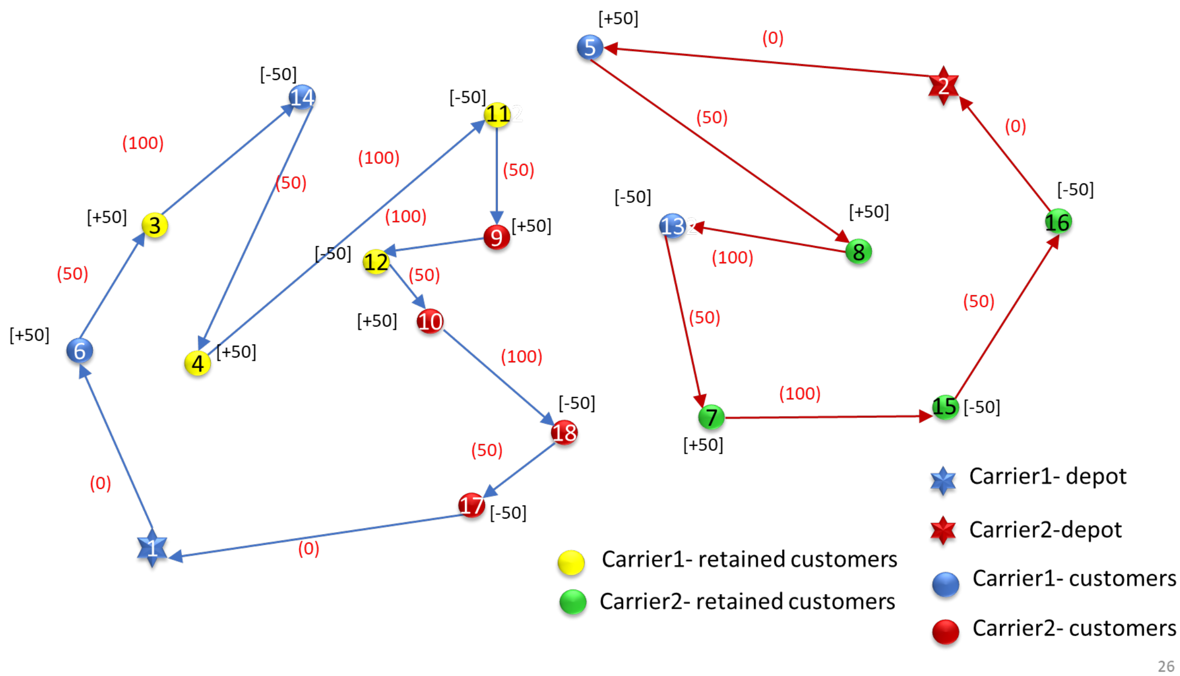

Figure 4.10: Vehicle route of the illustrative example – with collaboration

Two analyses have been done: 1) to calculate the total cost reduction due to carrier collaboration. 2) to understand how the cost reduction due to collaboration changes with the changes in percentage of jobs retained by the carriers. Fifteen hypothetical networks are solved for the first analysis. For all 15 instances, the jobs to be retained by each carrier is selected randomly and it is assumed that both carriers retain 50% of their received jobs. The vehicle capacity is assumed as 300 units for all vehicles and for all 15 instances. It is also assumed that all pickup and delivery is 50 units. The total transportation cost before and after collaboration for these 15 networks are shown in table 4.10. It is observed that the total transportation cost with collaboration is less than that of without collaboration in all 15 experiments. There is no specific trend in the percentage cost reduction is observed as the network size increases. This is due to the fact that the cost reduction in collaboration depends on the location of pickup and delivery nodes, number of retained jobs and location of pickup or delivery nodes of retained jobs. The percentage cost reduction is estimated by using Equation (35).

$$Percentage\ reducution = \left(\frac{\text{cost } before\ collaboration\ -\ \text{cost } after\ collaboration}{\text{cost } before\ collaboration}\right)\times 100 \qquad (35)$$

Table 4.10: Cost comparison of before and after collaboration

Instance	Network size (nodes)	Before collaboration			After collaboration	Percentage reduction
		Carrier - 1	Carrier – 2	Total		
1	20	138	201	339	306	9.73%
2	22	630	765	1395	1270	8.96%
3	24	872	744	1616	1362	15.72%
4	26	990	1033	2023	1606	20.61%
5	28	1042	650	1692	1326	21.63%
6	30	935	737	1672	1371	18.00%
7	32	1008	711	1719	1445	15.94%
8	34	988	1008	1996	1708	14.43%
9	36	754	1009	1763	1584	10.15%
10	38	1059	1182	2241	1912	14.68%
11	40	1177	1173	2350	1946	17.19%
12	42	1063	1162	2225	1891	15.01%
13	44	1128	1236	2364	1894	19.88%
14	46	1143	1410	2553	2159	15.43%
15	48	1263	1175	2438	2168	11.07%

Three networks of size 48 (Network1), 46 (Network2), and 44 (Network3) nodes are solved for the second analysis. Figure 4.11 shows the trend in which the percentage of cost reduction changes with the changes in the percentage of jobs retained by each carrier. The cost reduction due to collaboration is 22 to 28% when each carrier retains 10% of their jobs, whereas, it decreased to 18 to 23% for 40% job retention and to 5 to 13% for 70% job retention. This implied that, the cost reduction due to collaboration decreases as the number of jobs retained increases. The cost reduction for 10, 20, 30, 40, 50, 60, 70, and 80 percentage of job retention is shown in table 4.11.

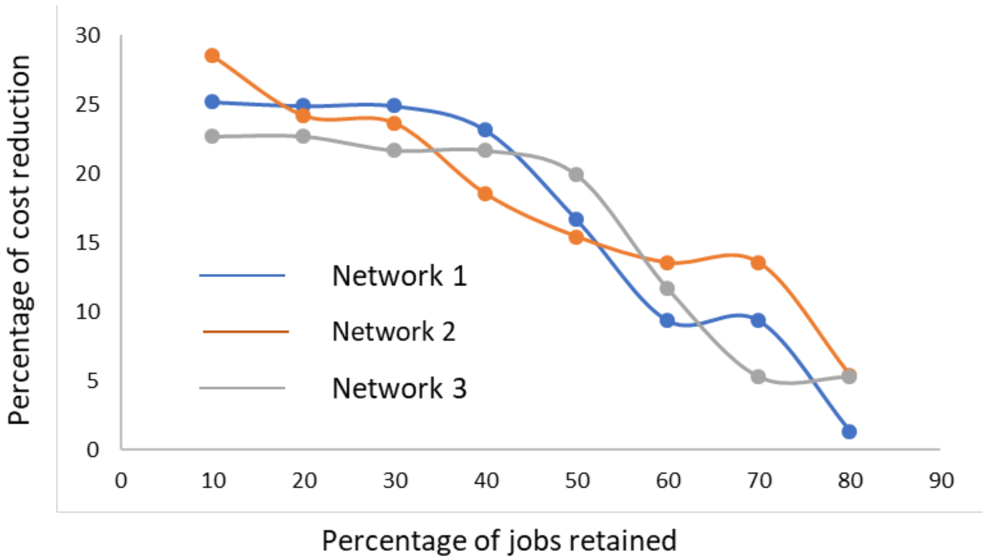

Figure 4.11: Changes in percentage cost reduction due to collaboration with the changes in percentage jobs retained

Table 4.11: Changes in percentage cost reduction due to collaboration with the changes in percentage jobs retained

percentage of jobs retained	Percentage of cost reduction due to collaboration		
	Network 1	Network 2	Network 3
10	25.18	28.52	22.67
20	24.90	24.21	22.67
30	24.90	23.66	21.66
40	23.13	18.53	21.66
50	16.65	15.43	19.88
60	9.35	13.55	11.68
70	9.35	13.55	5.33
80	1.35	5.41	5.33

CHAPTER 5
Summary and Conclusions

This project developed two mathematical programming models that can lead to improved efficiency of future freight transportation in South Carolina in the face of increasing demand and changes in the nature of the freight. These models addressed two elements of the freight transportation system from a strategic perspective when collaboration/coordination is used. The first model involves locating intermodal terminals while the second centers on first and last mile logistics.

This research is motivated by a confluence of changes that appears to be leading to an unacceptable situation in freight transportation in the U.S. and particularly South Carolina. It begins with the fact that the overall amount of freight being transported has been generally increasing for decades. Before eCommerce, most freight was transported on pallets from producer to customer including retail stores. The current freight transportation and material handling systems are predicted on this. eCommerce, on the other hand, deals in small orders involving a few "eaches," so the nature of freight is changing. Currently, the freight transportation system is rather inefficient and congested so scaling up for increased demand of smaller packages does not seem feasible. Collaboration and coordination to improve efficiency – especially horizontal collaboration where competitors collaborate to improve logistics – has potential. South Carolina has all of these elements based on location and major interstates; and also has the added disruptor of and increasing number of PANAMAX ships arriving that Port of Charleston. Quantitative planning tools are needed to make deliberate and measured decisions to remove impediments to economic growth due to transportation.

The math programming model for locating IMT's considers a freight network over a planning horizon with multiple products with different demands and package volumes. Rail and trucks are part of the transportation system and each have unique capacities. The IMT's each have a fixed cost to open, variable costs based on usage, and are required to remain open for the duration of the planning horizon one they are opened. To enhance realism, several features are included like the ability of a consignee to require freight from a specific supplier or any supplier. This model allows the decision maker to change the freight characteristics (total flow, IMT capacities, IMT locations, customer and supplier data, etc.) through the planning horizon and observe the flows and IMT's that minimize modeled costs. Finally, each IMT is allowed to hold freight for a short period of time to allow for limited consolidation/cooperation so that routing of some freight has the potential to be improved. The model was used to analyze contrived scenarios that allowed model validation and verification as well as exploring trends based on changing input factors. Some expected relationships between freight demand and container volumes were reported along with some less obvious results related to the availability of modes between IMTs and IMT capacity.

First and last mile logistics was modeled as an LTL pickup and delivery problem considering carrier collaboration with a centralized planner. The model assumes that each carrier has be ability to retain some pickup and delivery jobs to service themselves and release the rest to a common pool. The central planner then creates routes using the vehicles of all carriers that ensures both retained and pooled jobs are delivered at minimum cost. The model was solved for several instances and, as expected, the alliance provided a lower cost solution than if all carriers operate independently. The exact results are dependent on scenario parameters but cost reductions due to collaboration for the experiments in this study are about 20% when carriers retain 40% or less of their jobs and 10% when that number of much higher like 70%.

Based on these models, it seems highly likely that collaboration/coordination has the potential to positively impact the efficiency of freight flow. It is more certain that situation details are important because the different scenarios that parameterized each model created optimal solutions that varied quite dramatically in places. The conclusion is that these two cornerstones of a decision support framework are important and that output from quantitative models are required for decision makers to effectively plan for the future.

There next steps that are contemplated are: 1) improve both models to include important features that make them more realistic thereby improving the chances of implementation and 2) integrate the two models so that collaboration on first and last mile logistics is integrated with collaboration/coordination of longer-haul deliveries. For example, a carrier collaboration model written to maximize profit rather than minimize total cost is important because in analogous situation involving inventory, the optimal solution frequently requires one part to reduce profit for other to gain significantly more. Hence, this model would require addressing post-optimization profit allocation. For the IMT location and operations model, there are many options available to actual providers that have not been captures like dynamically adding capacity with different sized trucks. The way freight consolidation at the IMT's also needs to be modeled at a more sophisticated level.

The most intriguing next step is to integrate these models. This will create a model of the South Carolina freight network that will allow demands and supplies to be dynamically aggregated and disaggregated using horizontal collaboration in a way that minimizes costs, gives insight into the capacities required for the network over a long planning horizon, and informs decisions on infrastructure. This integrated model could provide South Carolina with a cutting-edge tool for making investments that support increased freight flow that is destined for the State, create business opportunities in this space that fosters economic development, and avoids exaggerating some of the negative consequences that will certainly be realized if the current system is simply scaled up.

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