DYNAMIC HYBRID CROSS-DOCKING MODEL WITH

MULTIPLE TRUCK TYPES

by

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Thesis Title: Dynamic Hybrid Cross-Docking Model with Multiple Truck Types

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Dedication

This thesis would not have been completed without the continuous support from my father, mother, husband, brother and grandparents. I dedicate my entire work to them as they were with me through each and every step of my educational path and were very supportive when it came to working on the thesis.

I would like to thank my colleagues at L'Oreal, who helped me tremendously when it came to working on my thesis. I dedicate this work to all my friends and family as well as those who have supported me and shared the long days and sleepless nights.

Finally, I dedicate this thesis to all the future ESM students, and I hope these students would find this thesis helpful in their work and help in seeking knowledge as well. I also thank God for giving me an opportunity to be a part of this university and to attend this program, and making this journey a memorable experience.

Abstract

In today's business environment, companies are forced to improve their logistics activities due to high competition. Therefore, improving the design and operations of distribution networks plays a very important role in efficiently managing supply chains. Usually, companies operate traditional distribution networks, which may not be economical for complex networks. Research and practice have been very inquisitive to find better ways to transport goods across locations. One way to improve distribution in such networks is through the use of cross-docks, which are intermediate facilities used to consolidate shipments. This research addressed the problem of optimizing the flow of goods between multiple supplier and multiple retailer terminals by taking complete advantage of the concept of hybrid cross-docking facilities. The objective of the developed model is to determine the best fleet dispatching and consolidation plans between the terminals using multiple truck types over a finite planning horizon. The objective function includes quantity dependent transportation cost components. The model is formulated as a mixed integer linear program and minimizes the total costs of transportation, throughput and inventory holding costs over the entire planning horizon. Sensitivity analysis is performed to assess the effect of varying the problem's parameters on the model's outputs. The results show that as the demand increases, there are more direct shipments using full truckload (TL) pickups, in order to ensure that the warehouse doesn't store bulky products. For large values of inventory holding costs and demand values, there seems to be little or no inventory of high volumetric weight products left at the warehouse. Most of the indirect shipments from cross-docks to retailers were for low volume products using TL trailers. Amongst all input parameters analyzed, changes in demand had the greatest effect on increasing leasing costs. However, changes in inventory holding costs were found to have a significant effect on decreasing the processing costs. Therefore, decision makers have to consider all the studied changes in parameters at the same time, in order to minimize the total system cost.

Search Terms: Supply Chain, Distribution Network, Logistics, Cross-docking, Sensitivity Analysis

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Chapter 1: Introduction

Many companies around the world are discovering a powerful source of competitive advantage through supply chain management (SCM), which comprises all of the integrated activities and processes that bring a finished product to the market and create satisfied customers. A supply chain is a system of people, organizations, information, activities and resources that is involved in helping to move a product or to deliver a service from the main supplier to the end customer. The end customer usually gets the finished product that is made from natural resources, raw materials and other components. SCM encompasses a wide range of topics within it, from manufacturing operations to purchasing to transportation and physical distribution of products. It links all of the partners in the supply chain. In addition to these departments, it also includes a few partners outside the organization such as the vendors, carriers, information system providers and the third party providers.

Within the organization, the supply chain can be broken down into different departments such as the physical distribution which encompasses data management, inbound and outbound transportation, and warehousing and inventory control activities. Sourcing, procurement, forecasting, production planning and scheduling and customer service are all part of the supply chain as well. In the recent past, managers have recognized that getting the products to customers faster than any competitors will improve the company's competitive position. Companies must seek new solutions to important supply chain management issues such as distribution network design, network performance analysis, load planning, and route planning, to remain competitive. Supply chain management becomes a tool to help achieve complex strategic corporate objectives. However, sometimes these objectives can be very conflicting. SCM is a tool to help reduce working capital, accelerate cash to cash cycles, take assets off the balance sheets, and increase inventory turns.

There are different opportunity areas in supply chain management, and each has its own benefits. These benefits individually can bring about cost savings and service enhancements, whereas collectively they can lead to breakthroughs in market share and profitability. One area of opportunity is distribution network optimization. Optimizing the distribution network brings about cost advantages. This breaks down into transportation savings and improvements in inventory carrying costs. Optimizing

a distribution network usually involves determining the best location for each facility, selecting the right carriers and setting the proper system configuration. Inventory management also plays an important role in SCM, and industrial and academic communities have formed many strategies in order to reduce total inventory cost. Vendor Managed Inventory (VMI) is one of the most popular strategies in inventory management. It is a business model in which the buyer of the product gives product information to the supplier and then the supplier takes full responsibility for maintaining inventory levels of the product at the buyer's location of consumption. It is a very successful concept used by many big box retailers such as Walmart [1]. The VMI methodology can reduce the demand variability in order to reduce the total inventory cost. The key to making a VMI work is shared risk.

Another very interesting supply chain initiative that has proven payback potential is cross-docking. It is the practice of receiving goods and processing them for distribution to customers in the shortest time possible with minimum handling and absolutely no storage in the facility. Figure 1 illustrates a pure cross-docking terminal [1]. This practice brings about potential savings over conventional warehousing. It uses the concept of consolidation of products from different suppliers intended to be distributed to one or more retailers. Also since there is no storage, it helps a great deal in reducing the inventory storage costs. Major retailers like Walmart use cross-docking to gain a huge competitive advantage over their competitors [1]. They introduced this concept in their system in the 1980s. It uses staging areas where the inbound goods are sorted, consolidated and stored until the outbound quantity is completed for shipment. The storage time is shorter than 24 hours. This strategy has helped Walmart streamline its supply chain from the point of origin to the point of sale by not only reducing the handling cost, but also by reducing the operating and storage costs. To track their sales and inventories, Walmart set up their own satellite system and is able to reduce unproductive inventories by allowing the stores to manage their stocks, reducing pack keys across many product categories and ensuring timely price markdowns.

In practice, there are different types of cross-docking methods used in industries. Among the different types of cross-docking methods, one of the most innovative and compromising approaches to cross-docking is the hybrid cross-

docking method as it provides some degree of storage to supplement the cross-docking operations.
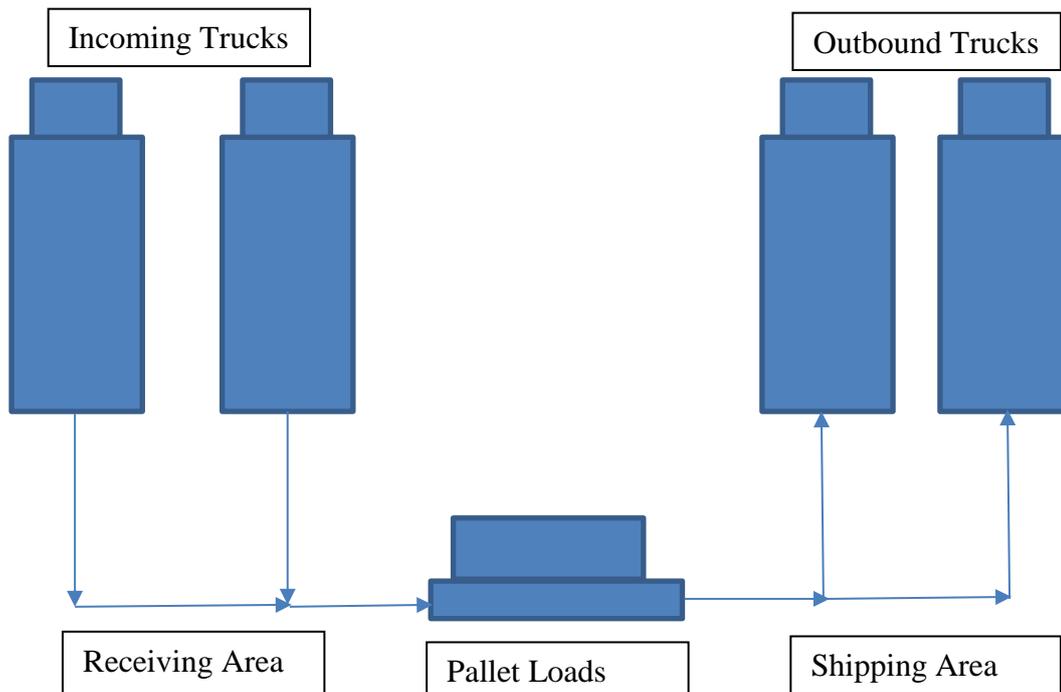
Figure 1: Pure Cross-Docking Terminal

In this case, the cross-docking terminal has a capacitated warehouse for the storage of incoming goods that are not shipped the same day. One or more products stored in the warehouse are blended with the incoming material, and then these completed palletized orders are loaded on outbound trucks [1]. A slight variation of this process involves some of the incoming products being routed to temporary storage at the warehouse while the rest is cross-docked. For the items that are not shipped immediately, racks are provided near the dock doors to facilitate the immediate retrieval of items. The hybrid cross-docking model is often used with high demand and high value products, as well as products that usually require small safety stock. This approach may also benefit the manufacturer to maintain economic production volumes while still fulfilling the needs of partners in the downstream supply chain [1]. Figure 2 illustrates a hybrid cross-docking terminal [1].

Shipment consolidation is another study opportunity in the area of supply chain. Shippers usually use two ways of transporting items using trucks: one is called the less-than-truckload shipment (LTL) and the other is called truckload shipment (TL). The former means that the shipped items do not take up the entire available

space on the truck and the latter means that the shipped items would fill up the entire capacity of the truck.
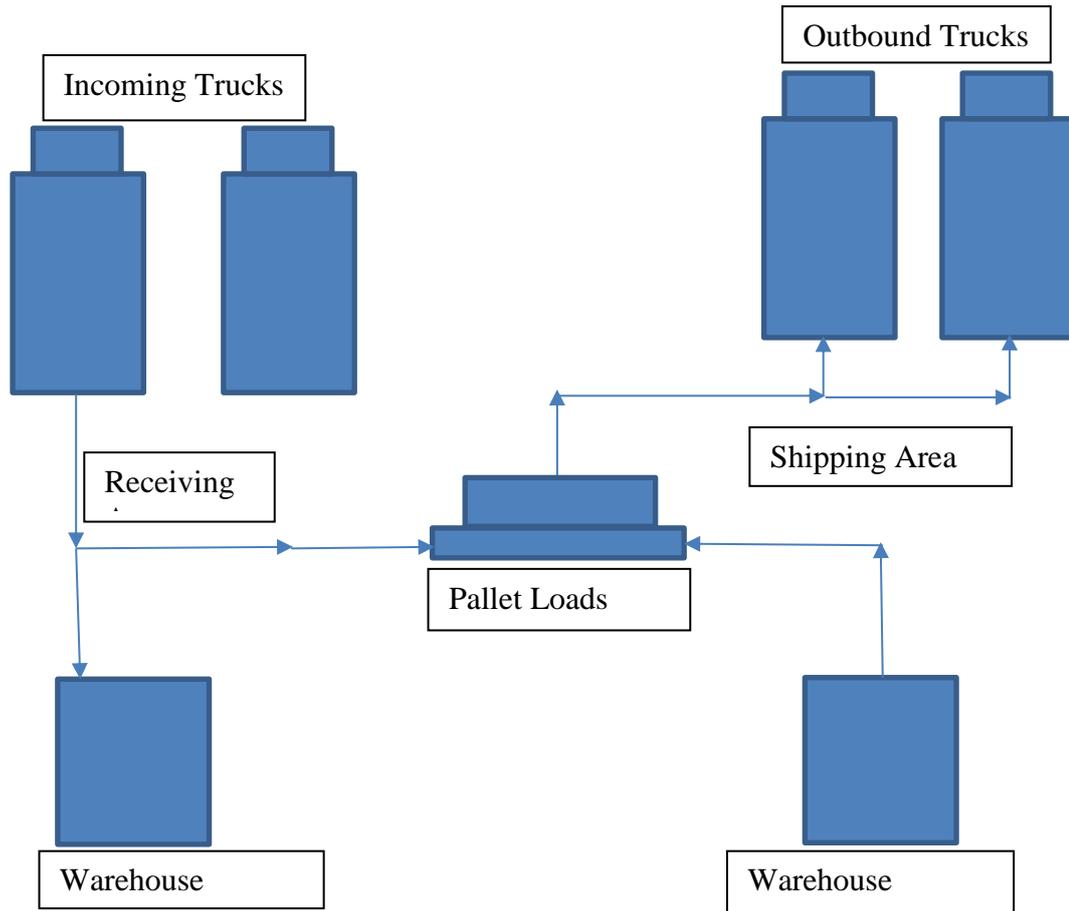
Figure 2: Hybrid Cross Docking Terminal

Shippers who offer TL shipments mainly cater to customers who try to ship in bulk. Consider an example of a company that has been delivering items from multiple plants using six different less-than-truckload (LTL) carriers. Through the use of a third party logistics provider, it will be able to consolidate the multi-vendor lots into two truckloads. By strategically consolidating the shipments, it helps in cutting the transportation costs by half. Also it helps reduce inventory levels, cut down on delivery times, improvise on time delivery, and enhance the product fill rates. Supplier management is another potential area of study in supply chain management. It works by involving the supplier during the product design and development stages. IKEA is one such example, whose furniture comes in simple to assemble kits that allow them to store the furniture in the same warehouse-like locations where they are displayed and sold.

Managing transportation in a supply chain is a huge area of concern for both customers and manufacturers. The parties that are involved are carriers and shippers. The modes of shipping include road, air, sea, and rail. We specifically look into truck shipments in this study. The major issues concerning truckload (TL) shipments are effective utilization of truck space and consistent service among different companies. The major issues concerning less than truckload (LTL) shipments are location of the consolidation facilities, vehicle routing and customer service. Shipments could either be direct from the supplier to customers or indirect through a distribution facility. Distributors add a lot of value to the supply chain. They bring about economies of scale in inbound and outbound transportation costs by combining shipments coming from several manufacturers to the same retailer. They also involve inventory aggregation at the distributor instead of individual retailer inventories. They also do a better job in shipment logistics with on time deliveries, shipment tracking and breaking bulk shipments. There are multiple tradeoffs while considering a transportation cost reduction. One of them is the tradeoff between transportation, facility and inventory costs. This usually involves the choice of the transportation mode and inventory aggregation. Another tradeoff is between transportation costs and responsiveness. There are many areas of transportation problems that are under study. One such area is the routing and scheduling in transportation which involves the assignment of trucks to demand points, sequencing the delivery points, and managing the exact time of visits/ unloading and loading.

In today's distribution environment, companies are forced to improve their logistics and supply chain networks due to high competition. There is a lot of pressure to manage Stock Keeping Units (SKUs) and have more frequent shipments of fewer items in less time due to customer demand for better service [2]. Improving distribution networks plays a very important role in supply chains as it has a huge impact on inventory reduction. Most companies apply a variety of distribution networks to transport various types of goods [3]. Most of the goods are transported from various suppliers to their Distribution Centers (DCs), and then to the retailers who require that specific good. With increased product proliferation, the average demand for individual product is decreasing but the variability in individual demand is increasing [4]. Additionally, logistics costs account for more than 30% of the sales dollar. Moreover, many companies in different industries (e.g. retail firms and less-

than-truckload (LTL) logistic providers) look for ways to minimize their total costs by reducing inventory at every step of the operation, including distribution.

Considering various problems in the area of the supply chain, this study mainly looks into the area of cross-docking which favors the timely distribution of freight, better synchronization with demand and a much more efficient usage of transportation assets. The main advantages involve minimization of warehousing cost and economies of scale in outbound flows (from the distribution center to the customers). With this method of distribution, the costly inventory function of a distribution center becomes minimal, while still sustaining the value-added functions of consolidation and shipping. Inbound flows are thus directly transferred into outbound flows in the short term with very little warehouse operations. Shipments characteristically spend less than 24 hours in the distribution center, sometimes even less than an hour. With cross-docking, goods are already assigned to a customer, and hence shipped as a truckload (TL). Cross-docking as a method of distribution that can be applied to many situations. In the case of manufacturing, it can be used to consolidate inbound supplies, which can be arranged to support just-in-time (JIT) assembly (parts for various stages of an assembly line). In the case of distribution, it can be used to consolidate the products coming from various suppliers and then can be delivered when the last inbound shipment is received. For transportation, it involves the consolidation of shipments from several suppliers (often in LTL carriers) in order to achieve economies of scale with truckload (TL). In the case of retailing, cross-docking looks into receiving products from multiple suppliers and then sorting them for outbound shipments to different stores. To date, a lot of research has been done on cross-docking problems varying from location and layout design of cross-docks to vehicle routing, dock door assignment and truck scheduling issues to temporary storage.

1.1 Research Objective

In this research, a supply chain of multiple suppliers providing multiple product types to multiple retailers is considered. The aim of this research is to optimize the flow of goods between the supplier-cross dock facility and the cross-dock facility-retailer terminals. We consider a hybrid cross-docking facility that is owned by a retailer, who is in charge of transporting these goods between the terminals. This hybrid facility houses a small capacitated warehouse inventory that is

required for temporal storage of certain goods. The developed supply chain model includes the quantity dependent transportation cost component in its objective function which hasn't been explored in the supply chain management literature. We consider both direct and indirect shipments, taking into consideration the *capacity* of the warehouse for temporal storage in a cross-docking facility, and also consolidation at the warehouses and cross-docks. Capacity at the supplier stage, which is specific for a product type, is considered to be unlimited.

The main aim of this work is to determine the load to be transported from origin to destination assuming that this load can come from different origins and be split and consolidated at the warehouses or cross-docks before reaching destinations. We also consider the availability of trucks which are owned by the retailer. The trucks are specific to each echelon, meaning they have specific truck types. The retailer can lease trucks from the market when they are short of their own, and similarly they can also rent out their trucks to the market to generate rental revenue. Transportation lead times are considered depending on the route. Also the processing time at the cross-dock facility is considered to be negligible. The objective is to meet the retailers' demand with no delays by trying to optimize the flow of goods between terminals and taking complete advantage of the cross-docking facility. It basically involves finding out the best fleet dispatching and consolidation plans between the terminals, so as to minimize the total costs of transportation, throughput and inventory holding costs over the entire planning horizon, by determining if the load is to be sent directly to customers or indirectly through cross-docks. The aim of this research is to better understand the process of hybrid cross-docking and enable a smooth distribution of products between suppliers and end retailers.

1.2 Research Significance

The main contributions of this research are as follows:

1. Supplement the cross-docking literature with a new model that considers multiple periods, multiple truck types and non-negative lead times using the concept of hybrid cross-docking.

2. Formulate the integrated problem as mixed integer linear model.

3. Provide an optimal transportation schedule for fleet dispatching using multiple truck types (whether using LTL or TL shipment), best consolidation plans at the cross-dock, and inventory storage decisions at the warehouse.

4. Assess the impact on cost structure achieved through the integration of the concept of multiple truck types and a hybrid cross-docking terminal.

1.3 Research Methodology

The following steps will be followed to solve the problem discussed in this research:

Step 1: Review the literature related to distribution systems, warehousing facilities, cross-docking, its types and various problems associated with it.

Step 2: Formulate the optimization model by defining the assumptions, objective function, decision variables, problem parameters and various constraints.

Step 3: Code the formulated model using CPLEX Optimization software.

Step 4: Perform sensitivity analysis to test the effect of the key problem parameters on the formulated model's outputs.

1.4 Thesis Outline

Chapter 1 introduced the research problem, the objective, its significance, and the methodology. Chapter 2 gives a brief introduction on cross-docking, types of cross-docking, cross-docking problems, and its various applications. Chapter 3 gives a detailed description of the problem under study. It explains the supply chain network in detail taking into consideration the quantity segment based transportation cost function. This chapter also details the mathematical model under consideration with specific highlights on the costs involved, the decision variables, parameters and constraints taken into consideration, along with some illustrative examples. Chapter 4 studies the effect of change of various sensitivity parameters on the performance of the model using various performance measures which are discussed in detail. Chapter 5 gives the results of the sensitivity analysis done on the experimental model taking various scenarios into consideration, and draws conclusions. The chapter also discusses the implications of this research on future research.

Chapter 2: Literature Review

In this chapter, a thorough literature review is performed on the different distribution systems, with specific focus on cross-docking and its various related activities. The first part explains cross-docking, its operations and their types. This is followed by a detailed review of the various strategic and operational problems involved in cross-docking.

2.1 Distribution Systems

As defined by Chopra [5], "Distribution refers to the steps taken to move and store a product from the supplier stage to the customer stage in the supply chain." It has a direct effect on the supply chain costs and customer experience and therefore has an impact on the overall profitability of a business. A good distribution strategy could be used to attain the objectives of a supply chain ranging from high responsiveness to low cost structure. This is why companies remain vigilant while selecting a distribution network. This requires decision makers to decide on the facilities to be built and their locations, such that the network will not just perform well with the current system state but will serve well for the facility's lifetime even when it is being exposed to changing environmental factors and market trends [6]. Facility location decisions are therefore very vital in strategic planning for a wide variety of firms. Therefore the design and operation of a physical distribution network involves selecting the best sites for intermediate cross-docking points [7]. Once the sites have been decided upon, the operations to, from and within the intermediate cross-docking points have to be optimized.

2.2 Warehousing Facility

Warehouses are physical locations where raw materials, work-in-process items, or finished products are stored and held as inventory. Companies can take advantage of the concept of managing a warehouse facility as it helps to meet increased customer demands, achieve economies of scale, and reduce the lead time required to deliver products. However, warehousing has some drawbacks. This type of operation is continuously under pressure to reduce the duration of the stay of products [8]. The longer the stay, the higher the costs associated with it (i.e. the inventory holding costs are high). Having a warehouse also introduces other problems such as opportunity costs, maintenance costs, and obsolescence costs. The major

functions of warehousing include receiving, putting away, storage, order picking, and shipping [9].

2.3 Cross-Docking

Cross-docking is defined as a materials handling and distribution strategy in which the materials flow from receiving to shipping with a primary objective of eliminating storage, excessive handling, and lead time, and minimizing transportation and storage costs while also maintaining the level of customer service [10]. It is basically a way to accelerate the product flow to minimize the lead time from suppliers to customers [11]. It is also an approach that helps in eliminating inventory level at the warehouse, as goods are not stored but moved from receiving dock to shipping dock. Cross-docking enables consolidation of differently-sized shipments to full truckloads, transported to the same destination, enabling economies in transportation costs. This is realized from another definition provided by [12]: "receiving product from a supplier or manufacturer for several end destinations and consolidating this product with other supplier's product for common final delivery destinations." This implies that products are transported indirectly from suppliers to retailers via cross-docks as opposed to direct shipment, where the products are transported directly from suppliers to retailers. It is an intermediate node in a distribution network that is committed to transshipments of truckloads alone [13]. As opposed to a warehouse, a cross-dock carries no stock or at least a significantly reduced amount of stock. In other words, warehouses, now as cross-docks, are transformed from inventory repositories to points of delivery, consolidation and pick-up [14, 15]. The focus now shifts from transshipping to not holding stock. This requires perfect synchronization between the inbound and outbound vehicles, which is quite difficult to achieve since most of the inbound shipments need to be sorted, consolidated and stored until the outgoing shipments are completed. This requires staging procedures. Therefore, cross-docking can be seen from another perspective as well. It is defined by Van Belle et al. [16] as "the process of consolidating freight with the same destination (but coming from several origins), with minimal handling and with little or no storage between unloading and loading of the goods." If these goods are to be stored, then it should be for a short period of time of approximately 24 hours [17, 18, 19].

In a retail distribution system, for example, the system would receive a single shipment of a number of truckloads of a given item. This incoming shipment would be unloaded from the inbound trucks, broken down, and reassembled in outbound trucks to the stores [10]. This immense application is credited to the fact that cross-docking improves the flexibility and responsiveness of the supply chain network while not requiring as much equipment investment as compared to the general distribution centers. As opposed to the warehousing system, here the vendors would have a prior request from the customers about the materials they need, such that as soon as the materials come to the cross-dock they can be transported to the required destination. The material handling operations of receiving and shipping represent the physical flow of products. Connected with this is the flow of information concerning the cross-docked product [4]. For many years, cross-docking has found an immense level of application in the retail sector. Many large retailers such as Walmart apply cross-docking which eliminates its inventory holding cost. Mailing companies like FedEx achieve cost effective transportation and Home Depot ensures transportation costs are reduced [11]. Therefore, the use of cross-docking operations has resulted in considerable competitive advantages given the high proportion of distribution costs for these industries. It shifts focus from "supply" chain to "demand" chain management [4].

2.4 Cross-Docking Operations

A terminal dedicated for cross-docking, called a "cross-dock", is usually a long, narrow rectangle shaped as an I, L, T or X [16]. The working area at a cross-dock can be classified into an import area and an export area [17]. These are where breakdown and buildup occur, respectively. Incoming cargo reaches the cross-dock at various times as they come from a number of suppliers. Cargo are either shipped directly or sent to the export area where they are loaded into outgoing containers. Outgoing cargo may then be shipped by vehicles having scheduled departure times, such as scheduled trains or aircraft. Each incoming (or outgoing) container has a due date and each outgoing (or incoming) container has a release time.

Generally, the retailer in a supply chain that utilizes cross-docking operations will place an order to the central office whenever it requires goods [3]. The central office then collects the orders from all retailers in its vicinity and places a purchase order (PO) with the respective suppliers. Consequently, suppliers send these

shipments to intermediate facilities called cross-docking facilities. Suppliers can either ship a full truckload (TL) or less-than-truckload (LTL) to the cross-dock facility. However, since suppliers look to minimize transportation costs, they prefer to fill an entire truckload (TL) rather than sending a less-than-truckload shipment the entire distance to the cross-docking facility. The cross-docking facility (CF) then consolidates all cargo going to the same distribution center and fills an outbound truck which remains docked at the CF until a) the truck has been waiting for a threshold-hour time window, or b) additional demand arrives for the truck to have a full load, whichever condition occurs first. Then the load is sent to its destination [3].

Any cross-docking center can be divided into three areas: loading, sorting, and unloading areas as shown in Figure 3 [20]. Incoming trucks arriving at the yard of the cross-dock are directly assigned to a receiving door until and unless all of them are occupied, then they have to wait in a queue in the yard until assignment. Once they are docked, supplies (i.e., pallets, packages, or boxes) from the inbound trailer are unloaded and scanned. All of the supplies contain bar codes which reveal their identification. In some systems, the goods are also weighed and labeled at the receiving dock. Then, goods are taken over by a material handling device, such as a worker operating a fork lift in retail industries, case and pallet conveyors in mail distribution centers, tilt tray sorters, stretch wrappers, or automated guided vehicle systems [2, 4]. The goods are then forwarded to the designated shipping door, where they are loaded onto an outbound truck which serves the designated destination. Once it is completely loaded, the trailer is removed from the dock and replaced by another trailer and this course of action repeats.

Cross-docking is usually applied to those companies that deal with huge volumes of merchandise or the ones that serve a large number of stores [20]. It handles a high volume of items in a short period of time. There are many advantages to the cross-docking approach. It streamlines the supply chain operations from the point of origin to point of sale (POS). The literature provides several advantages of cross-docking as compared to traditional distribution centers and warehouses and point-to-point deliveries [13, 21, 22].
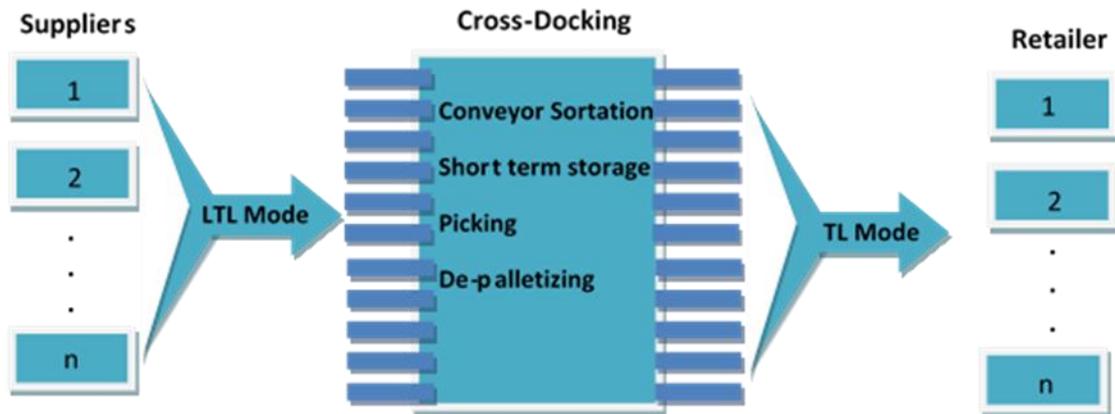
Figure 3: Cross-Docking Terminal

Some of the advantages of cross-docking are as follows: shorter delivery lead time (from supplier to customer), reducing storage area, reduction in costs (labor, inventory holding, warehousing, handling), fewer overstocks, lesser concern of risk for loss and damage, faster inventory turnover and also enhanced customer service. When compared with point-to-point deliveries, the advantages include cost reduction (labor and transportation), better use of resources (full truckload), shipment consolidation, and also a better match between shipment quantities and actual demand.

2.5 Types of Cross-Docking

Different types of cross-docking operations have been developed and used based on various factors such as operating market, demand rate, level of demand uncertainty, and company strategy. Generally, any cross-docking operation can be categorized under "Manufacturing Cross-Docking," "Distributed Cross-Docking," or "Terminal Cross-Docking" [23].

Manufacturing Cross-Docking includes transporting those products that are moved right off the production line to a waiting truck or those products produced that are to be staged for later shipment. Distributed Cross-Docking distinguishes between "current/active," "current/same," and "future" items. "Current/active" deals with items that are loaded right away to a vehicle, while "current/same" deals with products that are staged on a conveyer belt and which will be released later that day. "Future" holds the items until they become current/same day. Products from distribution centers are sent to the cross-dock for shipment of mixed loads to

customers. This category falls into Terminal Cross-Docking. Each type of mentioned cross-docking system should be selected based on different factors such as "Product Property," "User Demand," and "Facility Capacity" [8]. Clearly, not all products are suitable for cross-docking, not only because of their life cycle and volume but also because managers prefer to have some safety stock kept in warehouses rather than utilizing a pure cross-docking approach.

Cross-docking faces many challenges in the distribution environment. These are not disadvantages, but they are certain issues that any company that is trying to apply cross-docking in its supply chain has to consider. The factors that influence the suitability of cross-docking systems are not only the product type and its level of demand uncertainty, but also other factors such as "Unit Stock-Out Costs" and "Demand Rate." "Unit Stock-Out Costs" refers to the cost of lost sales on a single unit of product, whereas products are categorized from the "Demand Rate" perspective based on having a "stable and constant demand rate" or an "unstable or fluctuating demand rate" [4].

Cross-docking would be preferred for items that have low unit stock-out costs and stable and constant demand. However, cross-docking can still be implemented even while having a constant demand rate but high stock-out costs. However, care should be taken with precise planning systems to ensure that the instances of lost sales are kept to a minimum.

Success of cross-docking operations also depends on equipment and manpower [4]. Hence, the selection and management of appropriate skilled manpower and equipment becomes critical to cross-docking operations. In other words, one of the aims of cross-docking is to minimize required manpower and equipment by eliminating storing and picking activities. However, material handling at the cross-docks is quite complicated and labor intensive [10]. Therefore, extra care should be taken to optimize the personnel requirement to deal with the variety of items handled by different processes. The layout and design of the receiving and shipping areas are also major factors for a cross-docking system [4]. A well-designed and well-equipped dock can process all of the mentioned activities in a faster and more efficient way. In the cross-docking facility, each carton or pallet from an incoming truck must be accurately identified at receipt, allocated instantaneously to a purchase order and then routed to an appropriate outbound door for delivery. The whole process has to be

done as quickly as possible, which does not leave any room for possible errors. Therefore, it is also crucial to manage the flow of information as accurately as the flow of goods. According to [20], one of the concerns of management in cross-docking should be to design information systems or software to manage and speed up the cross-docking operations.

2.6 Cross-Docking Problems

Cross-docking practitioners have to deal with many decisions that are to be made during the design, tactical and operational phase of the cross-docks [16]. These decisions have to be taken seriously, as they can have a major impact on the efficiency of the system. The literature gives a brief description of the various cross-docking decision problems studied. Some of these decisions have an effect on a longer term; these are known as strategic or tactical decisions. Those that deal with short term decisions are known as operational decisions. The next section describes these decisions in detail which have been dealt with in the literature.

2.6.1 Strategic Decisions. This section describes papers that deal with the strategic assessment of the location of the cross-docks and the best layout for the cross-docks.

2.6.1.1 Location of cross-docks. The design of a distribution network involves finding out the location of one or more cross-docks, with a strategic decision to be made on their position. This problem of locating the cross-docks has attracted a lot of attention in recent years. Initial studies on the location of cross-docks have been performed by Sung and Song [24]. The authors found out which of the possible cross-docks are to be opened and operated and how many vehicles are needed on each arc in order to minimize the total costs. It assumed consolidation only at one cross-dock. A similar transportation problem was carried out by Musa, Arnaout, and Jung [14], where they minimized the total shipping costs by finding out the best way to load and route the trucks in the network by considering direct shipment as well. Gumus and Bookbinder [23] studied a similar problem by further taking multiple product types into consideration. They considered possible consolidation at both manufacturers and cross-docks; throughput costs at cross-docks were also investigated for multiple types of products, and the costs for in-transit inventory. They formulated optimization models to minimize total costs and provide solutions to medium sized networks. A completely different approach was taken by some other authors [25, 26, 27]. They

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considered a multi-echelon distribution network design problem in which goods (from multiple product families) had to be transported from the central manufacturing plant to the different distribution centers, and from there delivered to customers via cross docks. This problem was solved in two stages, with the first stage focusing on locating the distribution centers and cross-docks and the second stage deciding the required quantity of product families that needed to be transported from the plant to distribution centers and transshipped to cross-docks from warehouses and then distributed to customers.

2.6.1.2 Layout design. Once the location is known, another strategic decision that needs to be made is to choose the layout of the cross-dock. A study on this was conducted by Bartholdi and Gue [28]. They focused on the shape of a cross-dock and how its shape affected the performance of the cross-dock. They hinted to the fact that the layout depends on the size of the facility and the pattern of goods flow inside. Another study on the design of the storage space for temporary storage of incoming freight was dealt with by Vis and Roodbergen [22]. They suggested that the storage areas have to be designed with the aim of enabling easy access to the loads and fast transportation of loads to the loading docks.

2.6.2 Tactical Decisions. Once the cross-dock(s) is (are) available, decisions have to be made regarding how the goods flow through a network of cross-docks ensuring supply meeting the demand and minimizing the total costs. This section describes the papers that dealt with this problem.

2.6.2.1 Cross-docking networks. This research dealt with the determination of the flow of goods through a network of cross-docks to reduce the costs and make supply meet demand [16]. Lim et al. [29] focused on extending the transshipment problem by allowing temporary storage with the aim of minimizing holdover inventory. This problem assumed that supplier and customer time windows and flow were constrained by warehouse capacities and transportation schedules. This transportation is provided by flexible or fixed schedules and lot sizing is handled through multiple shipments. A similar study was carried out by Chen et al. [15] by considering a multi-commodity flow problem. Küçükoğlu et al. [30] studied the cross-docking transportation problem where the products were sent from the suppliers to customers through the cross-docks without storing them for long time. They considered two-dimensional truck loading constraints for different sized products to

find exact capacity of each truck. Buijs et al. [31] presented a new classification scheme for cross-docking research based on inputs and outputs for each cross-docking problem aspect.

2.6.3 Operational decisions. This section describes the papers that focus on the day-to-day decisions to be made in the system. The operational decisions discussed are that of Vehicle Routing, Dock Door Assignment and Truck Scheduling, and Temporary Storage.

2.6.3.1 Vehicle routing. The vehicle routing problem deals with the pickup and delivery processes. The first approaches were taken by [32, 33]. The aim was to find an optimal vehicle routing schedule for both processes, assuming that all the pickup vehicles arrive at the cross-dock at the same time so as to prevent waiting times for the outbound trucks in order to minimize the transportation costs and fixed costs of the vehicles. Wen et al. [18] explained the vehicle routing problem with cross-docking (VRPCD), where a homogeneous fleet of vehicles are used to carry orders from the suppliers to the customers via a cross-dock. The orders are consolidated at the cross-dock but do not allow intermediate storage. The main objective is to minimize the overall travel time by respecting the time window constraints at the centers and a time period for the whole transportation operation. Ahmadizar et al. [34] studied the cross-docking problem with the aim of assigning products to suppliers and cross-docks. They optimized the schedules of outbound and inbound vehicles by minimizing the total costs of purchasing, transportation and holding costs. Moghadam et al. [35] presented a vehicle routing and scheduling problem in a network of supplier, customers and cross-docks. They assumed a set of homogenous vehicles with limited capacities to transfer products between terminals that must be visited within their time windows.

2.6.3.2 Dock door assignment and truck scheduling. Dock door assignment problems deal with allocation of each dock door to an inbound or outbound truck arriving at the cross-dock. Tsui and Chang [36] presented a general model of the dock door assignment which assumes that all shipments go directly from inbound to outbound trucks with no storage at the cross-dock. The model also assumed a mid-term horizon and the designation of strip and stack doors are fixed. This approach was extended by Cohen and Keren [37], where the model is adapted to allow goods for a particular destination to be split and delivered to multiple doors allocated to that

destination. Bartholdi and Gue [38] modeled the travel cost and the three types of congestion normally experienced in a cross-docking terminal and built a layout to minimize workers' travel cost as well as congestion time.

The truck scheduling problem deals with "where" and "when" the trucks should be processed at the terminal, which consists of assigning the trucks to dock doors and finding out the docking schedule for all trucks and doors. Some of the research related to this has been carried out by Yu and Egbelu, and Boysen et al. [20, 39]. They considered settings in which a terminal consists of just a single inbound and outbound door. Boloori Arabani et al. [40] studied meta-heuristics to find the best sequence of inbound and outbound trucks, in order to minimize the total operation time. They dealt with a cross-docking system having temporary storage facility, but concentrated mainly in establishing coordination between the performances of inbound and outbound trucks. Alpan et al. [41] dealt with a transshipment scheduling problem in a multiple dock door cross-docking warehouse, in order to minimize the sum of inventory holding and truck replacement costs. Lim et al. [16] dealt with the short-term scheduling problem. They looked into material handling inside the terminal for a particular truck schedule. Once all the trucks have been docked, all handling operations have to be assigned to resources in such a way that all operations at the cross-dock are carried out efficiently. Miao et al. [42] studied scheduling procedures where trucks are assumed to be given service time windows, which are maintained as hard constraints. Boysen [43] studied a special truck scheduling problem covering the requirements of zero inventory cross-docking terminals of the food industry, dealing with refrigerated products that cannot be stored at cross-docks. Dondo et al. [44] introduced a new mixed-integer-linear programming formulation for the vehicle routing problem with cross-docking to find the routing and scheduling of a mixed fleet, the truck docking sequence, the dock door assignment and the travel time to move the goods through the cross-dock. Mohtashami et al. [45] proposed a model that minimizes the make-span, transportation costs and the number of truck trips in the entire supply chain.

2.6.3.3 Temporary storage. Sometimes due to the imperfect synchronization of the inbound and outbound vehicles and also because the goods do not arrive in the same sequence in which they must be loaded, these goods have to be stored in the cross-docks for a while. Some of the literature dealt with this operational problem of

where to store the incoming products. An initial study was performed by Vis and Roodbergen [22], where they found temporary storage locations for the incoming goods that would minimize the total travel distance of the goods within the cross-dock. The storage areas have to be designed with the aim of enabling easy access to the loads and fast transportation of loads to the loading docks. However, they do not look into any transshipment decisions. Sandal [46] determined which staging strategy is more suitable for a cross-docking operation as a function of goods attributes and container-loading requirements. It uses simulation to evaluate many staging strategies in order to support the optimal loading of the outbound trucks.

2.6.4 Other related issues. Some of the other characteristics are summarized in the following papers. The loading and unloading procedures are accompanied by a team of workers and equipment. Lim et al. [17] studied the scheduling of internal resources for the same, by processing each truck as close as possible to its due date (Just-In-Time). Yan and Tang [11] analyzed two distinctive cross-docking operations which are pre-distribution cross-docking operations (Pre-C) and post-distribution cross-docking operations (Post-C). The differential operational performances are examined and compared, and they conclude saying that the suitability of Pre-C and Post-C are sensitive to environmental operational factors such as the uncertainty of demand, the unit inventory holding cost and storage cost, and unit operation cost at the cross-dock. Also, Magableh et al. [3] presented a generic simulation model of cross-docking operations that could be expanded to other cross-docking facilities. It was used to study the effect of growing demand through the cross-docking facility. Bellanger et al. [47] worked on optimizing a cross-docking system which is modeled as a three-stage hybrid flow shop, in which shipments and orders are represented as batches. They proposed a branch-and-bound algorithm to find a schedule that minimizes the completion time of the latest batch.

2.7 Chapter Summary

As can be noticed from the preceding literature review, many papers addressed vehicle routing, truck scheduling, temporary storage, transshipment and other related operational decisions. But even the papers that addressed temporary storage problems, they mainly only dealt with staging strategy decisions and truck docking sequences for cross-docking operations. Yu and Egbelu [20], Borooni Arabani et al. [40] studied truck scheduling problems by considering a cross-docking system with temporary

storage. However, they did not consider multiple truck types and any transshipment decisions. Alpan et al. [41] studied a transshipment scheduling problem in a multi dock door cross-docking warehouse. However, they did not take multiple product types into consideration. Even the papers that addressed transshipment problems, did not consider any temporary storage decisions. Gumus and Bookbinder [23] worked on a transshipment problem by considering possible consolidation at both manufacturers and cross-docks, with multiple product types. However they did not consider transportation lead times and temporary storage decisions. Musa, Arnaout, and Jung [14] did not take into consideration multiple truck types and storage decisions in their study. Küçükoğlu et al. [30] studied a transshipment problem, but did not include direct shipping from suppliers to retailers as well as temporary storage decisions in their study. Based on the above review of the literature and to the best of our knowledge, this study is the first to combine the concepts of transshipment and temporary storage decisions in a cross-docking operation. This study is the first to address the problem of optimization of the flow of goods between multiple supplier and multiple retailer terminals, taking complete advantage of a hybrid cross-docking facility and aiming to find the best fleet dispatching and consolidation plans between the terminals using multiple truck types over a finite planning horizon. It uses a quantity-dependent transportation cost component in its objective function which hasn't yet been explored in the supply chain management literature.

Chapter 3: Model Formulation

A supply chain of multiple suppliers providing multiple product types to multiple retailers is considered. Flow of goods from suppliers to retailers may be direct or through a number of hybrid cross-docks. The end consumer demand for each product types is time-varying and realized at the retailers. A retailer owns the cross-dock facilities and is in charge of transporting goods in the supply chain. Locations of the cross-dock facilities are known. Each of those facilities incorporates a small capacitated warehouse used for temporal storage.

There are specific vessel types in the retailers' fleet, and each vessel type has its own fixed operating cost per period and fixed capacity. These vessel types differ and are specific for each echelon, due to the difference in the shipping bulk in each echelon. The number of vessels owned by the retailer for each vessel type in each echelon is constant and known. Those numbers cannot be changed as we don't consider tactical/strategic decisions. However, if required, the retailer can lease a vessel from the market in each period at a fixed cost. Similarly, retailers' idle vessels in each period are for rent in the market and generate rental revenue. It is to be noted that the vessels leased from the market and the ones rented to the market differ from one another and are specific to each echelon.

A number of time periods make up the planning horizon for the retailers' facility. The demand of each retailer in each period for each product type must be met by shipments from cross-docks and by direct shipments from the suppliers. There are also transportation lead times depending on the route. We assume that the lead time on all routes between suppliers to cross-docks, and between cross-docks and retailers is the same. Lead time on those routes is regarded as an average value which is assumed to be the same on both the supplier-cross dock, and cross dock-retailer network. Lead time for a direct shipment is also assumed to be a fixed time period independent of the shipment's origin and destination. Lead times on direct shipment routes are greater than the lead times on all other routes. We assume that the processing time at cross-dock facilities is negligible and therefore we do not include it in this model.

The retailers' aim is to minimize the total cost of transportation, throughput, and inventory holding for the entire planning horizon. Holding cost is charged against

the stock of each product type at the warehouse unit in each period. Throughput cost is charged against each item that goes through the cross-docking process in each period.

Transportation cost includes fixed costs and cost of leasing additional trucks from the market. Fixed cost of transportation is the cost of operating the truck independent of the route. We apply a quantity-dependent transportation cost function as shown in Figure 4 for the case of four quantity segments. This transportation costing is based on real life industry data (in this case, the source is from an international cosmetic industry) and is approximated to real life data values.
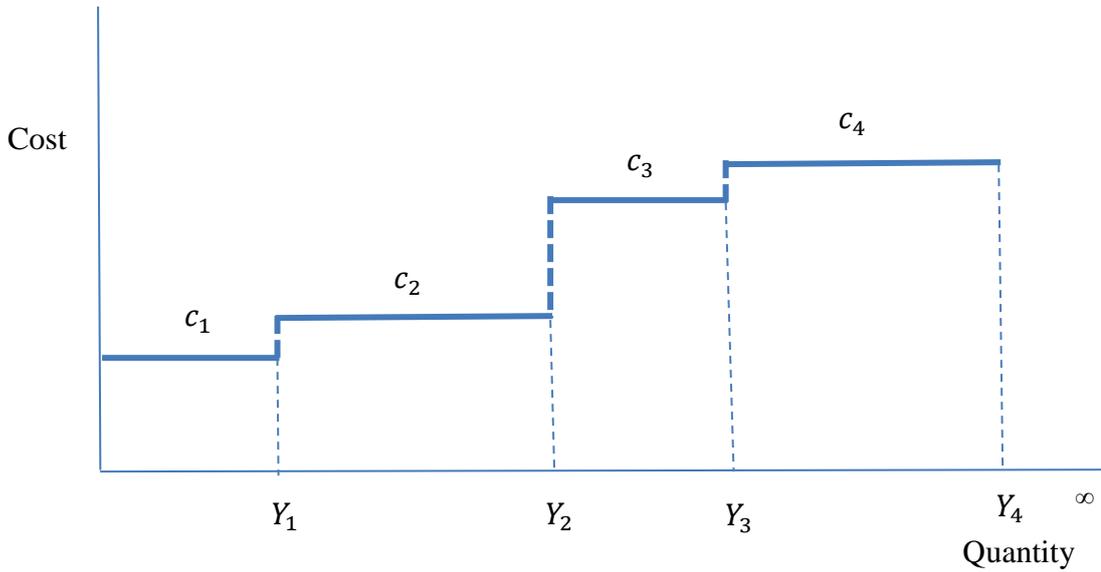
Figure 4: Quantity Segment for Transportation Function

If a retailer orders Q units, then the transportation cost function (considering any arc) is determined by c_1 (a fixed cost for shipping a small quantity in the first segment) and then c_2 (fixed cost for shipping a larger quantity in the second segment), and y_i (cut off quantities for each segment) as follows:

G (Q) = c_1 , if $0 < Q^w_{any\ arc} < y_1$ and

c_2 , if $y_1 < Q^w_{any\ arc} < y_2$

The cost of maintenance of these trucks is negligible as we assume that the number of trucks owned is known. Each truck has a weight capacity, and each product type has a weight used to calculate the total load in a truck. Note that the fixed operating cost of a truck applies to all trucks whether owned or leased from the market. Cost of leasing a truck is a separate cost. The unused vehicles of the retailer can be rented to the market, and the rental revenue generated is deducted from the

total cost of transportation. The retailer needs to optimize utilizing its own trucks first before they start renting trucks from the market. Therefore, we assume that revenue generated by renting a truck to the market is less than the cost of leasing a truck from the market.

We assume that suppliers have unlimited capacity. Each supplier may offer multiple product types. We assume that product types offered by a supplier are not offered by other suppliers in the supply chain. In order to simplify this, we include a capacity parameter for each supplier which is unlimited for the products offered by the supplier, and zero for the other product types.

3.1 Problem Formulation

In this section, the decision problem is formulated as a mixed integer linear program.

Indices

i: supplier zone, (i= 1,2,…,I)

j: cross-dock (j= 1,2,…,J)

k: retailer (k= 1,2,…,K)

l: product type such that $l \in L$, L set of product families

t: time period number (t= 1,2,..,T), which is in days

a: index for the modified all unit discount segment (a= 1,2,..,A)

Variables

q_{ijlt}: Quantity of product l shipped from supplier i to CD facility j in period t in a truck

q_{jklt}: Quantity of product l shipped from CD facility j to retailer k in period t in a truck

q_{iklt} : Quantity of product l shipped from supplier i to retailer k in period t in a truck

R_t^{SC}: Number of rented trucks between supplier-cross dock terminals in period t

R_t^{CR}: Number of rented trucks between cross dock-retailer terminals in period t

R_t^{SR}: Number of rented trucks between supplier-retailer terminals in period t

S_{ijta}^{ij}: Binary variable for quantity segment a for arcs i to j in period t

S_{jkta}^{jk}: Binary variable for quantity segment a for arcs j to k in period t

S_{ikta}^{ik}: Binary variable for quantity segment a for arcs i to k in period t

T_{ijt}^{ij}: Number of trucks owned and released by retailer in period t between i-j

T_{jkt}^{jk}: Number of trucks owned and released by retailer in period t between j-k

T_{ikt}^{ik}: Number of trucks owned and released by retailer in period t between i-k

H_{ijt}^{ij}: Number of trucks leased and used specifically in period t between i and j

H_{jkt}^{jk}: Number of trucks leased and used specifically in period t between j and k

H_{ikt}^{ik}: Number of trucks leased and used specifically in period t between i and k

I_{jlt} : Inventory at the CD facility j for product l at the end of period t

Parameters

D_{klt}: Demand for product l from retailer k in period t

Y_a^{ij}: Quantity cut off for segment a in echelon $i - j$

Y_a^{jk}: Quantity cut off for segment a in echelon j - k

Y_a^{ik} : Quantity cut off for segment a in echelon i - k

S_{jl}^w: Storage capacity of the warehouse unit at facility j for product l in each period

S_{jl}^{cd}: Processing capacity of the cross-docking unit at facility j for product l in each period

S_{il}^s : Capacity of supplier i for product l in every period

h_{jl}^w: Inventory holding cost per period for product l at the warehouse unit of CD facility j

h_{jl}^f: Processing cost for product l at the facility j

w_l : Volumetric weight of product type l

C_a^{ij}: Fixed cost of transporting units in echelon i - j in segment a

C_a^{jk}: Fixed cost of transporting units in the echelon j - k in segment a

C_a^{ik}: Fixed cost of transporting units in the echelon $i - k$ in segment a

F^{ij}: Fixed cost of leasing truck specific for echelon i - j from the market in any period

F^{jk}: Fixed cost of leasing truck specific for echelon j - k from the market in any period

F^{ik}: Fixed cost of leasing truck specific for echelon i - k from the market in any period

R^{ij}: Fixed revenue of renting truck from echelon i - j to market in any period.

R^{jk}: Fixed revenue of renting truck from echelon j - k to market in any period

R^{ik}: Fixed revenue of renting truck from echelon i - k to market in any period

Note that: $R^{ij} < F^{ij}$, $R^{jk} < F^{jk}$, $R^{ik} < F^{ik}$

LT_{ij} : Lead time (in periods) on all arcs i to j

LT_{ik} : Lead time (in periods) on all arcs j to k

LT_{ik} : Lead time (in periods) on all arcs i to k

M^{SC}: Total number of trucks owned by retailer for echelon i - j in every period

M^{CR}: Total number of trucks owned by retailer for echelon j - k in every period

M^{SR}: Total number of trucks owned by retailer for echelon i - k in every period

S^{capij}: Capacity of truck specific for echelon i - j

S^{capjk}: Capacity of truck specific for echelon j - k

S^{capik}: Capacity of truck specific for echelon $i - k$

Objective Function

$$Min\ Z = \sum_t^T \sum_i^I \sum_j^J \sum_a S_{ijta}^{ij} C_a^{ij} + \sum_t^T \sum_j^J \sum_k^K \sum_a S_{jkta}^{jk} C_a^{jk} + \sum_t^T \sum_i^I \sum_k^K \sum_a S_{ikta}^{ik} C_a^{ik} +$$

$$\sum_i^I \sum_j^J \sum_t^T H_{ijt}^{ij} F_H^{ij} + \sum_j^J \sum_k^K \sum_t^T H_{jkt}^{jk} F_H^{jk} + \sum_i^I \sum_k^K \sum_t^T H_{ikt}^{ik} F_H^{ik} + \sum_i^I \sum_j^J \sum_l^L \sum_t^T q_{ijlt} h_{jl}^f +$$

$$\sum_j^J \sum_l^L \sum_t^T I_{jlt} h_{jl}^w - \sum_t^T R_t^{ij} R^{ij} - \sum_t^T R_t^{jk} R^{jk} - \sum_t^T R_t^{ik} R^{ik}$$

The first three cost components capture the fixed cost of transporting units specific to each echelon in segment *a*. The next three cost components are the total cost of leasing trucks from the market which is specific for each echelon. The next component is the total processing cost of cross-docked items at the cross-docks. The eighth component is the total cost of goods storage at the warehouse unit of cross-docks. The last three components are the total revenue generated by renting trucks to market.

Constraints

1. Total load shipped on each arch i-j, j-k, and i-k in each echelon cannot exceed the total truck capacity for each echelon-specific truck on those arcs in each period:

$$S^{capij}(T_{ijt}^{ij} + H_{ijt}^{ij}) \ge \sum_l w_l q_{ijlt} \qquad \forall\, i, j, t$$

$$S^{capjk}(T_{jkt}^{jk} + H_{jkt}^{jk}) \ge \sum_l w_l q_{jklt} \qquad \forall\, j, k, t$$

$$S^{capik}(T_{ikt}^{ik} + H_{ikt}^{ik}) \ge \sum_l w_l q_{iklt} \qquad \forall\, i, k, t$$

2. The retailer owns a fixed number of trucks for each echelon in every period, whether they are being used or rented to the market:

$$M^{SC} = R_t^{SC} + \sum_{t-LTij}^{t} \sum_{i,j} T_{ijt}^{ij} \qquad \forall \, t$$

$$M^{CR} = R_t^{CR} + \sum_{t-LTjk}^{t} \sum_{j,k} T_{jkt}^{jk} \qquad \forall \, t$$

$$M^{SR} = R_t^{SR} + \sum_{t-LTik} \sum_{i,k} T_{ikt}^{ik} \qquad \forall \, t$$

3. Retailers' demand for each product type in each period must be met by direct shipments from suppliers and indirect shipments from cross-docks:

$$D_{klt} = \sum_{j}^{J} q_{jkl(t-LT_{jk})} + \sum_{i}^{I} q_{ikl(t-LT_{ik})} \quad \forall \, k, l, t$$

4. Inventory balance at the warehouse unit of a CD for each product type:

$$I_{jlt} = \sum_{i}^{I} q_{ijl(t-LT_{ij})} + I_{jl(t-1)} - \sum_{k}^{K} q_{jklt} \quad \forall \, j, l, t$$

5. Warehouse unit has a storage capacity for each product type:

$$I_{jlt} \leq S_{jl}^{W} \quad \forall \, j, l, t$$

6. Each CD facility has a cross-docking (processing to prepare shipments) capacity for shipments directed to retailers:

$$\sum_{k}^{K} q_{jklt} \leq S_{jl}^{cd} \qquad \forall \, j, l, t$$

7. Each supplier has a capacity for each product type (in applying the model, infinite capacity for the product types belonging to the supplier, and zero for the remaining product types), in every period:

$$\sum_{j}^{J} q_{ijlt} + \sum_{k}^{K} q_{iklt} \leq S_{il}^{s} \quad \forall \, i, l, t$$

8. LTL Shipping Constraints: The quantity transported in each arc lies in one or more of the quantity segments for the transportation function:

$$Y_{(a-1)}^{ij} S_{ijta}^{ij} \leq \sum_{l} q_{ijlt} * w_l \leq \sum_{a} Y_{a}^{ij} S_{ijta}^{ij} \quad \forall \, i, j, t, a$$

$$Y_{(a-1)}^{jk} S_{jkta}^{jk} \leq \sum_{l} q_{jklt} * w_l \leq \sum_{a} Y_{a}^{jk} S_{jkta}^{jk} \quad \forall \, j, k, t, a$$

$$Y_{(a-1)}^{ik} S_{ikta}^{ik} \leq \sum_{l} q_{iklt} * w_l \leq \sum_{a} Y_{a}^{ik} S_{ikta}^{ik} \quad \forall \, i, k, t, a$$

9. Mutually Exclusive Constraint: The quantity transported in each arc should lie in any one of the segments:

$$\sum_a S_{ijta}^{ij} = 1 \quad \forall\, i,j,t$$

$$\sum_a S_{jkta}^{jk} = 1 \quad \forall\, j,k,t$$

$$\sum_a S_{ikta}^{ik} = 1 \quad \forall\, i,k,t$$

10. Sign constraints:

$S_{ijta}^{ij}\; S_{jkta}^{jk}\; S_{ikta}^{ik}$ – Binary variables

$T_{ijt}^{ij}\; T_{jkt}^{jk}\; T_{jkt}^{jk}\; H_{ijt}^{ij}\; H_{jkt}^{jk}\; H_{ikt}^{ik}\; R_t^{ij}\; R_t^{jk}\; R_t^{ik}$ – Integer variables

$q_{ijlt}\; q_{jklt}\; q_{iklt}\; I_{jlt}$ – Continuous variables

The developed model is a mixed integer linear program with *IJTA + JKTA + IKTA* binary variables, *IJLT + JKLT + IKLT + JLT* positive variables, 2(*IJT + JKT + IKT*) + 3*T* integer variables, and 4(*IJT+JKT+IKT*) + 6*T* + *KLT* + 4*JLT* + *ILT* + 2(*IJTA+JKTA+IKTA)* + *IJLT* + *JKLT* + *IKLT* constraints. The illustrative example as well as the problems in the sensitivity analysis section will be solved using the CPLEX optimization solver. Table 1 summarizes the number of variables and constraints obtained as the problem size increases.

**Table 1: Number of variables and constraints for different problem sizes**

Case						Problem Size	No. of binary variables	No. of continuous variables	No. of integer variables	Constraints
S	CD	R	Product	Period	Segment					
2	2	2	2	2	8	256	192	56	54	588
2	3	2	2	2	8	384	224	76	70	716
2	2	3	2	2	8	384	256	72	70	768
3	2	2	3	2	8	576	256	108	70	826
4	2	3	4	3	10	2880	520	232	110	1556
3	2	2	3	2	18	1296	576	108	64	1466

3.2 Illustrative Example

In this section, we consider an example of a local retailer that has its stores spread across different locations within a country. This retailer owns a hybrid cross-docking facility which provides some degree of storage to supplement the cross-docking operations. It offers a variety of products that come from different suppliers. This retailer may own trucks that are used to transport goods between the supplier and retailer terminals. There may be cases when they own insufficient trucks or no trucks at all, and that's when they can lease trucks from the market for the transportation of goods. The retailer could also rent out idle trucks to the market and generate revenue. The main aim of the retailers' facility is to meet the demand needs of the retailers with no delays, by trying to optimize the flow of goods between the terminals.

We now assume a supply chain with 2 suppliers, 2 cross-docks and 2 retailers to illustrate the model developed in the previous section. Figure 5 visualizes the proposed network for this example. Since each supplier is specific to a particular product type, in this case we have only two products. The planning horizon covers two time periods. The cut off quantities for each segment in each echelon are considered to be different as we consider two different types of trucks used for each echelon. In this case we consider 8 different segments as listed in the tables below. The two different types of trucks used are trailers and pickups. The trailer is 13.4m in length, 2.6m in height and 2.4m in width, around $70m^3$ in volume. The pickup has a capacity of $20m^3$ and is 6.1m in length, 2.5m in height and 2.2m in width. The pallets considered are standard euro pallets which are $1m^3$ in size. The various parameters considered in this model are explained in Tables 2-5 and have been chosen based on real life industry data (in this case, the source is from an international cosmetic industry) and are approximated close to the real life data values. The demand is considered to be uniformly distributed and ranging between 0 to 100 cartons. Each carton is measured in volumetric weight (m^3). The storage capacity of the warehouse and the processing capacity at the cross-docks are considered to be unlimited. Since the storage capacity is product-specific, it is measured in terms of the number of cartons, and so is the processing capacity as well. The weight is defined in terms of the volumetric weight of a carton of a standard product type, and the size of the carton depends on the type of product *l*. In this case we are considering two product types, each having volumetric weights of 0.1 and $0.2m^3$. The inventory holding cost is

charged per m^3 per day at the warehouse. Hence, the total inventory cost would be dependent on the volumetric weights of the products. The processing cost for a product is the cost of handling a product, and in this case, every time a carton is picked from the rack or placed back there, there is a handling cost that is charged per m^3 per day. Considering the echelon *ij*, the fixed cost of transporting 15m^3 volume of products using a trailer, which would classify as the first segment, is considered to be 196 dollars and this would be the cost of a less-than-truckload (LTL) shipment. The second segment is then followed by an increase of 22 dollars, making it a total of 218 dollars to ship 70m^3 volume of products, thereby making it the cost of a truckload (TL) shipment. The third segment will cost 414 dollars to ship 85m^3 volume of products, and hence will charge for one less than a truckload (LTL) shipment and one truckload (TL) shipment and so on. The same pattern is followed for the other two echelons as well. Considering the echelon *ij* again, the fixed cost of transporting 5m^3 volume of products using a pickup, which would classify as the first segment, is considered to be 125.5 dollars and this would be the cost of a less-than-truckload (LTL) shipment. The second segment is then followed by an increase of 10.5 dollars, making it a total of 136 dollars to ship 20m^3 volume of products, thereby making it the cost of a truckload (TL) shipment.
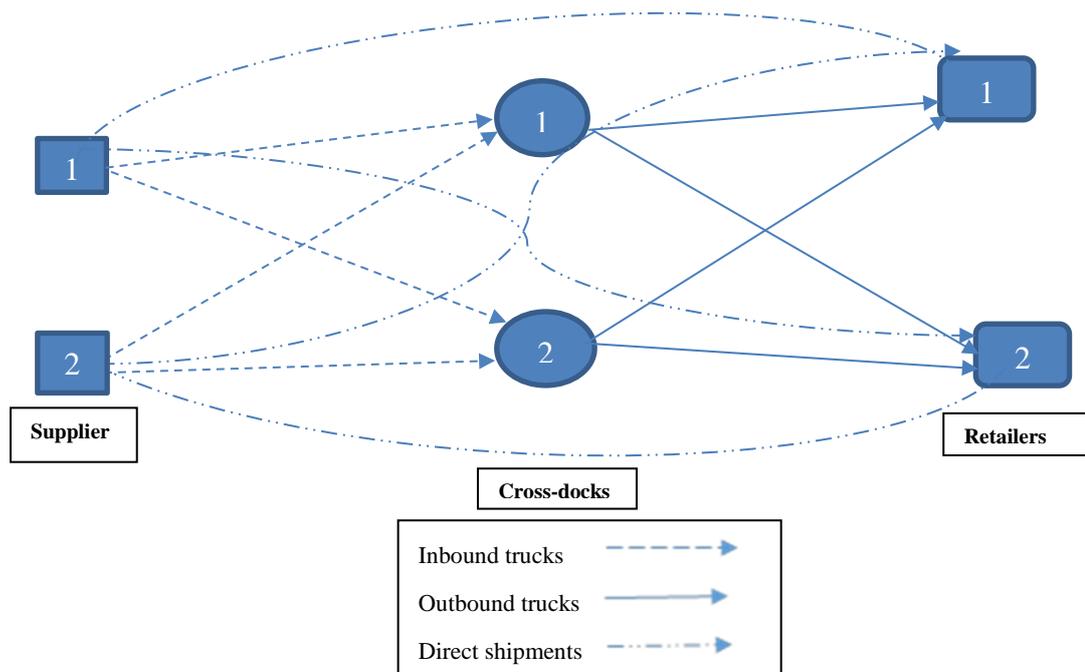
Figure 5: Proposed network

This will mean that the third segment will cost 261.5 dollars to ship 25m³ volume of products in that segment, and hence will charge for one less than truckload (LTL) shipment and one truckload (TL) shipment and so on. The same is applicable for the other two echelons as well. The fixed cost of leasing a truck is dependent on the ultimate destination and usually the revenue that is generated from renting the trucks to the market depends on the customer requirement. All costs are reported in dollars. Here the average lead time for direct shipments is considered to be 1 time period. The major assumption in this model is that the lead time for indirect shipments is considered to be less than the time period, and therefore assumed to be zero. The fixed cost of transporting the units depends on whether a trailer or a pickup is used. The total number of trucks owned by the retailer for each echelon in every period is fixed. Also since two types of trucks are available for all echelons, there are two truck capacities for all echelons. The supplier storage capacity is assumed to be unlimited for the type of product it supplies. The below Tables 2-5 summarize the values taken into consideration for all the parameters. We coded the model using GAMS platform in CPLEX optimization software and ran it on a computer with a 2.1 GHz processor and 8 GB RAM. Solving each problem took only a few seconds.

Table 2: List of all model parameters and their values for illustrative example 1

Parameter	Values
D_{klt} (number of cartons)	$D_{111} = 17, D_{112} = 84, D_{121} = 55, D_{122} = 30$
	$D_{211} = 29, D_{212} = 22, D_{221} = 35, D_{222} = 86$
S_{jl}^w (number of cartons)	$S_{11}^w = 5470, S_{12}^w = 8501$
	$S_{21}^w = 11987, S_{22}^w = 19051$
S_{jl}^{cd} (number of cartons)	$S_{11}^{cd} = 34,734, S_{12}^{cd} = 27,868$
	$S_{21}^{cd} = 8921, S_{22}^{cd} = 24,192$
h_{jl}^w (\$ per carton per day)	1.36
h_{jl}^f (\$ per carton)	2.72
w_l (m³)	$w_1 = 0.1$ and $w_2 = 0.2$
S_{il}^s (number of cartons)	Assumed to be large (considered as sum of demand from each retailer of every product type in every time period)

Table 3: Truck parameters for illustrative example 1

	Total number of trailers and pickups owned by the retailer for each echelon in every period respectively	Truck Capacities of trailer and pickup respectively (m^3)
Arcs i-j	3 trailers (period 1) , 3 trailers (period 2) 2 pickups (period 1), 2 pickups (period 2)	Trailer: 70 , Pickup: 20
Arcs j-k	3 trailers (period 1) , 3 trailers (period 2) 2 pickups (period 1), 2 pickups (period 2)	Trailer: 70 , Pickup: 20
Arcs i-k	2 trailers (period 1) , 2 trailers (period 2) 2 pickups (period 1), 2 pickups (period 2)	Trailer: 70 , Pickup: 20

Table 4: Cut off quantities for segments 1 to 8 for each truck type in all echelons

Parameter	Truck type	Cut off quantities for segments 1 to 8
$Y_a^{ij}, Y_a^{jk}, Y_a^{ik}$	Trailer	15, 70, 85, 140, 155, 210, 225, 280
$Y_a^{ij}, Y_a^{jk}, Y_a^{ik}$	Pickup	5, 20, 25, 40, 45, 60, 65, 80

Table 5: Cost parameter values for illustrative example 1

Parameter	Fixed cost of transporting units in segments 1 to 8 using trailer and pickup respectively ($ per shipment load)	Fixed cost of leasing truck from market & Fixed cost of renting truck to market in any period ($ per truck)
$C_a^{ij}, C_a^{jk}, C_a^{ik}$	Trailer:196,218,414,436,632,654,850,872 Pickup:125.5,136,261.5,272,397.5,408, 533.5,544	Trailer: 485, 435 Pickup: 322, 272

Results

The following results were obtained after running the first case:

Table 6: Results of cost structure for illustrative example 1

		Cost Structure			
Case $i*j*k*t$	Transport cost ($)	leasing cost ($)	Inventory cost ($)	Processing Cost ($)	Total cost ($)
2*2*2*2	898	0	45.97	153.41	-7331.62

The first illustrative example resulted in a total cost of $ -7331.62. This implies that a higher revenue of $ 8429 is generated as compared to the costs incurred. The tables below summarize the quantity of each product transported in each arc in every period, and the kind of trucks used for the transportation of products between echelons. This also gives an understanding of whether a TL or an LTL shipment was used for the transportation. Illustrative example 1 resulted in no direct shipments using pickups and no shipments in echelons *jk* and *ik* respectively using trailers. Hence they are not listed in the tables below. The total volume of each product that is transported from each supplier to each retailer in every period is calculated, which will help in classifying if the shipment released in that specific arc is a TL or an LTL shipment. In Table 7, 206 cartons of product 2 were shipped from supplier 2 to cross-dock 2 in time period 1. Product 2 has a volume of 0.2 m^3 and hence the total volume shipped in that arc is 41.2 m^3. Since this lies in the second segment of the transportation function for the trailers, it is 1 TL shipment.

Table 7: Quantity variables for the *i-j* network using trailers

i	*j*	*l*	*t*	q_{ijlt}	V_{ijlt}	LTL/TL Shipment
1	1	1	1	0	0	
1	1	1	2	0	0	
1	1	2	1	0	0	
1	1	2	2	0	0	
1	2	1	1	0	0	
1	2	1	2	0	0	
1	2	2	1	0	0	
1	2	2	2	0	0	
2	1	1	1	0	0	
2	1	1	2	0	0	
2	1	2	1	0	0	
2	1	2	2	0	0	
2	2	1	1	0	0	
2	2	1	2	0	0	
2	2	2	1	206	41.2	1 TL
2	2	2	2	0	0	

As for the network i-j using pickups, 152 cartons of product 1 were shipped from supplier 1 to retailer 2 in time period 1 (see Table 8). Product 1 has a volume of 0.1 m^3 and hence the total volume shipped in that arc is 15.2 m^3. Since this lies in the second segment of the transportation function for the pickups, it is 1 TL shipment.

Table 8: Quantity variables for the i-j network using pickups

i	j	l	t	q_{1ijlt}	V_{1ijlt}	LTL/TL Shipment
1	1	1	1	0	0	
1	1	1	2	0	0	
1	1	2	1	0	0	
1	1	2	2	0	0	
1	2	1	1	152	15.2	1 TL
1	2	1	2	0	0	
1	2	2	1	0	0	
1	2	2	2	0	0	
2	1	1	1	0	0	
2	1	1	2	0	0	
2	1	2	1	0	0	
2	1	2	2	0	0	
2	2	1	1	0	0	
2	2	1	2	0	0	
2	2	2	1	0	0	
2	2	2	2	0	0	

As for the network j-k using pickups, Table 9 shows the quantities released in each arc in each time period. Table 10 shows the total volume of products 1 and 2 shipped across to different retailers. In this case it resulted in 4 TL shipments as the total quantity for each product lies in the second segment of the transportation function for the pickups. So out of the 16 trailers available, only 1 trailer was used for transportation in echelon ij, and the rest were rented to the market. Out of the 12 pickups available, 5 pickups (1 in ij and 4 in jk) were used for transportation and the rest were rented to the market (see Table 11).

Table 9: Quantity variables for the j-k network using pickups

j	k	l	t	q_{jklt}	V_{jklt}
1	1	1	1	0	0
1	1	1	2	0	0
1	1	2	1	0	0
1	1	2	2	0	0
1	2	1	1	0	0
1	2	1	2	0	0
1	2	2	1	0	0
1	2	2	2	0	0
2	1	1	1	17	1.7
2	1	1	2	84	8.4
2	1	2	1	55	11
2	1	2	2	30	6
2	2	1	1	29	2.9
2	2	1	2	22	2.2
2	2	2	1	35	7
2	2	2	2	86	17.2

Table 10: Total quantity and volume for the *j-k* network using pickups

j	k	t	q_{1jklt}	V_{1jklt}	LTL/TL shipment
2	1	1	72	12.7	1 TL
2	1	2	114	14.4	1 TL
2	2	1	64	9.9	1 TL
2	2	2	108	19.4	1 TL

Table 11: Trailer and pickups rented for the *ij, jk,* and *ik* networks

Truck type	t	R_t^{SC}	R_t^{CR}	R_t^{SR}
Trailer	1	2	3	2
	2	3	3	2
Pickup	1	1	0	2
	2	2	0	2

The trailer and pickups used in the case study are truckload shipments (TL). Table 12 shows a breakdown of the TL shipments used for this case.

Table 12: Summary of truck types leased and breakdown of LTL/TL shipments for illustrative example 1

Truck type	Total no: of truck types	Breakdown of trucks used in each echelon			LTL/TL shipments		
		ij	jk	ik	ij	jk	ik
Trailer	16	1	0	0	1 TL		
Pickup	12	1	4	0	1 TL	4 TL	

No trucks were leased from the market as the retailer aims at utilizing its own trucks first, and hence there is no leasing cost incurred. This case resulted in no direct shipment, all the shipments were indirect, meeting the needs of the retailers' demands. There is a total of 222 units that is left over as inventory in period 1 and this is shipped out from the cross-dock in period 2 (see Table 13).

Table 13: Inventory left over at the cross-dock in each period

j	l	t	I_{jlt}
1	1	1	0
1	1	2	0
1	2	1	0
1	2	2	0
2	1	1	106
2	1	2	0
2	2	1	116
2	2	2	0

In the second illustrative example, the same case as above is considered. We assume all parameters are the same as the previous illustrative example, with only an additional assumption that this time the retailer owns no trucks and hence there would be no trucks rented and only trucks are leased from the market to transport products. The retailer outsources its transportation function to a third party, and tries to concentrate on its core competencies like the production, storage and maintenance activities.

Results

The following results were obtained after running the second case:

Table 14: Results of cost structure for illustrative example 2

Case i*j*k*t	Transport cost ($)	Leasing cost ($)	Inventory cost ($)	Processing Cost ($)	Total cost ($)
			Cost Structure		
2*2*2*2	898	2095	45.97	153.41	3192.38

This case resulted in a total cost of $3192.38. Since the retailer owns no trucks, no trucks were rented and hence no revenue was generated. There were a total of 1 trailer and 5 pickups that were leased for the transportation of products between the echelons. The trailer was a TL shipment and out of the 5 pickups, there were 4 TL shipments in arcs *jk* and 1 TL shipment in arc *ij*. This case resulted in no direct shipments; all the shipments were indirect, meeting the needs of the retailers' demands.

In the third illustrative example, the same base illustrative example is considered along with the same parameters, but this time we assume that the cut off quantities for each segment in each echelon is the same as we consider just one type of truck used for all echelons (in this case we are using trailers only). All the trailers here are owned by the retailer. We also assume the lead times for direct and indirect shipments to be negligible, or less than a time period.

Results

This case resulted in a total cost of $ -2038.62. It implies that a higher revenue of $3480 is generated as compared to the costs incurred. Out of the 14 trailers owned, 2 TL trailers were used in arcs *ij*, and 4 TL trailers were used in arcs *jk*. The rest of the 8 trailers were rented to the market.

Table 15: Results of cost structure for illustrative example 3

Case i*j*k*t	Transport cost ($)	Leasing cost ($)	Inventory cost ($)	Processing Cost ($)	Total cost ($)
			Cost Structure		
2*2*2*2	1242	0	45.97	153.41	-2038.62

No trucks were leased from the market as the retailer aims at utilizing its own trucks first, and hence there is no leasing cost incurred. This case resulted in no direct shipment, all the shipments were indirect, meeting the needs of the retailers' demands.

In the fourth illustrative example, the same case as the base illustrative example is considered along with the same parameters with the only exception: that in this case, each echelon consists of just one type of truck allotted to it, with echelons *ij* and *ik* allotted to the trailer and echelon *jk* allotted to the pickups. All the trailers here are owned by the retailer.

Results

The following results were obtained after running the fourth case:

Table 16: Results of cost structure for illustrative example 4

Case	Transport	Cost Structure			
i*j*k*t	cost ($)	Leasing cost ($)	Inventory cost ($)	Processing Cost ($)	Total cost ($)
2*2*2*2	980	0	45.97	153.41	-2300.62

This case resulted in a total cost of $ -2300.62. This means a total revenue of $3480 was generated. There were a total of 2 TL trailers and 4 TL pickups that were used for the transportation of products. The rest of the 8 trailers were rented to the market from all echelons together in periods 1 and 2. However, no pickups were rented, as all the trucks owned were utilized for the transportation of goods. No trucks were leased from the market and hence there is no leasing cost incurred. This case resulted in no direct shipment; all the shipments were indirect, meeting the needs of the retailers' demands.

In the last illustrative example, the same case as above is considered with the only difference being that no trucks are owned by the retailer. The retailer tries to maximize its core competency operations and hence outsource the transportation function to a third party. We assume all parameters are the same as the previous illustrative example.

This case resulted in a total cost of $ 3437.38. Since the retailer owns no trucks, no trucks were rented and hence no revenue was generated. There were a total

of 2 TL trailers and 4 TL pickups that were leased for the transportation of products (Table 17).

Table 17: Results of cost structure for illustrative example 5

Case *i*j*k*t*	Transport cost ($)	Leasing cost ($)	Inventory cost ($)	Processing Cost ($)	Total cost ($)
				Cost Structure	
2*2*2*2	980	2258	45.97	153.41	3437.38

3.2.1 Analysis of the results of the illustrative examples. The results of the 5 illustrative examples are presented in this section along with explanations regarding these results. Different performance measures like the cost structure, the total number of trucks used and the number of LTL and TL shipments were studied and compared between different cases. It is to be noted that all these cases were run considering low demand values.

The first study was conducted between the case that owns alternative truck types for all echelons with a lead time of 1 time period for direct shipments (illustrative example 1), and the case that has alternative truck types for all echelons with a lead time of 1 time period for direct shipments and assuming no trucks are owned (illustrative example 2). Since example 1 rents out the extra trucks owned, there is a considerable amount of revenue generated and this brings the total cost down (see Figure 6).
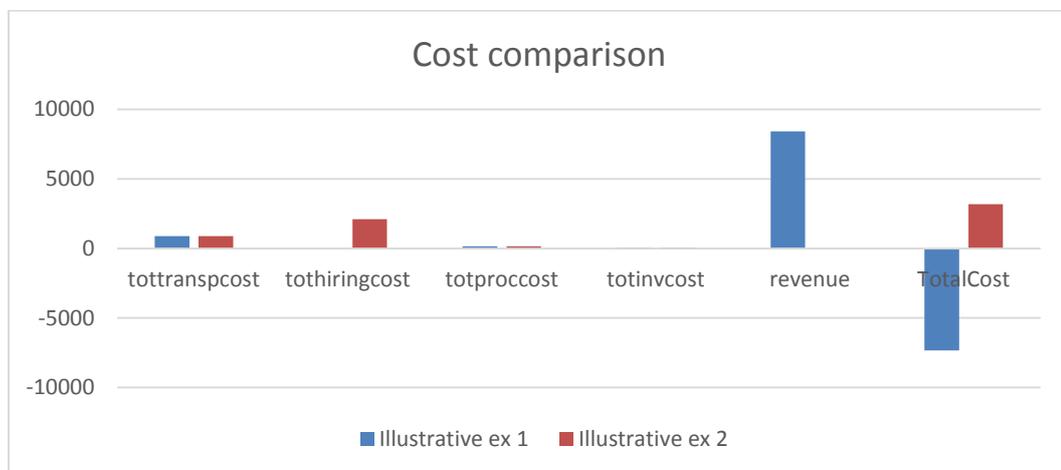
Figure 6: Cost comparison study of illustrative examples 1 and 2

In example 2, there is a considerable amount of leasing cost generated. However, the revenue generated by renting out trucks in example 1 is much higher

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than the costs incurred for leasing the trucks in example 2. In this case it is better that the retailer owns its own trucks. The study on LTL vs. TL shipments (see Figures 7 and 8) shows that mainly TL trailers and TL pickups were used and leased in examples 1 and 2, respectively.
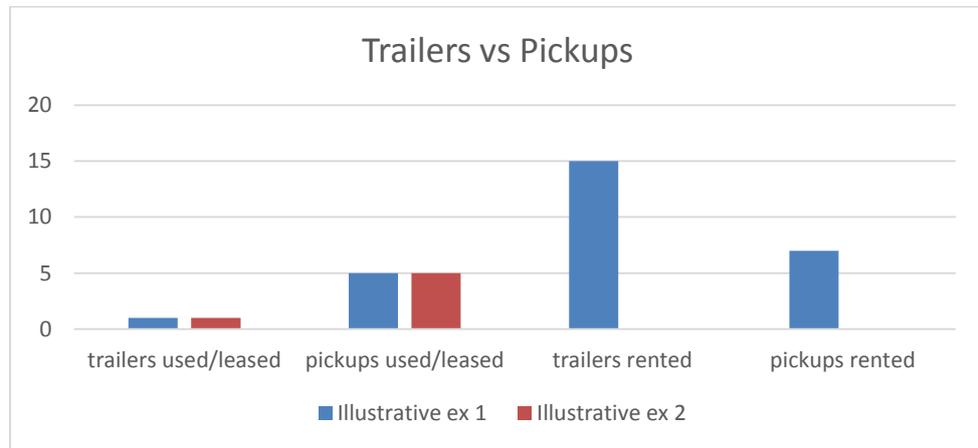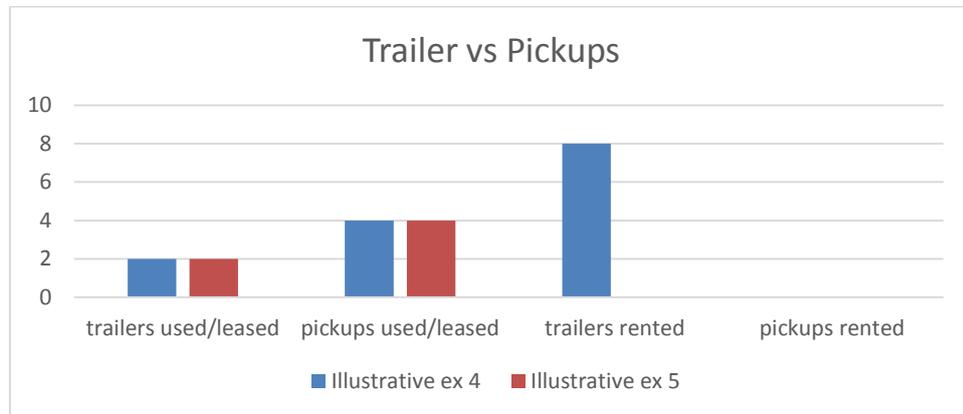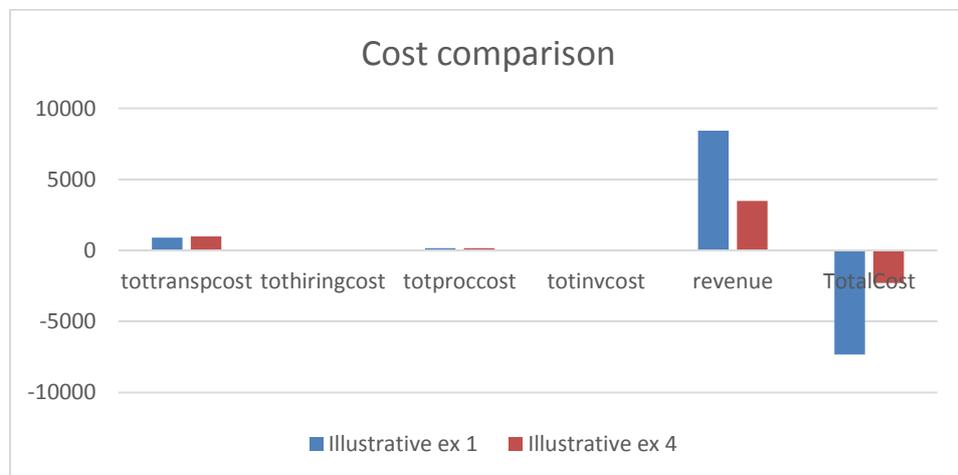

Figure 7: Study on number of trailers and pickups
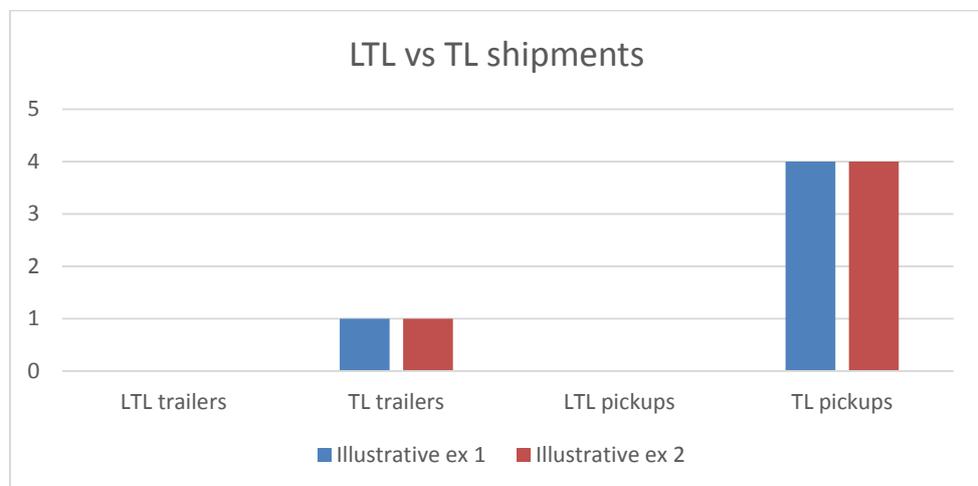
Figure 8: Study on the number of TL and LTL shipments

The second study was conducted between the case that owns specific truck types for each echelon with a lead time of 1 time period for direct shipments (illustrative example 4), and the case that uses specific truck types for each echelon with a lead time of 1 time period for direct shipments and assuming no trucks are owned (illustrative example 5). Since example 4 rents out the extra trucks owned, there is a considerable amount of revenue generated and this brings the total cost down (see Figure 9). However, the revenue generated by renting out trucks is not is not as high as in the case when we had alternative truck types. This revenue does not really offset the costs incurred by leasing trucks from the market.

Therefore in this case, it wouldn't matter if the retailer outsourced its transportation function to a third party and concentrated instead on its core operational functions. In this case as well, mainly TL pickups and trailers were used or leased to transport products (see Figures 10 and 11).
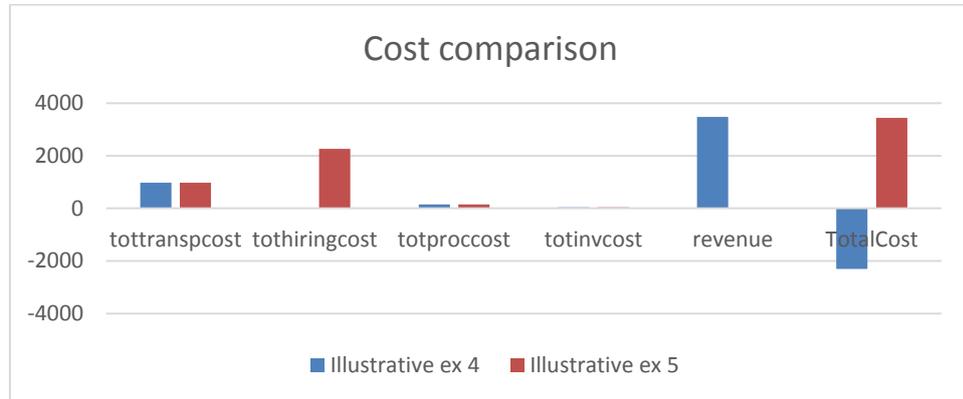
Figure 9: Cost comparison of illustrative examples 4 and 5

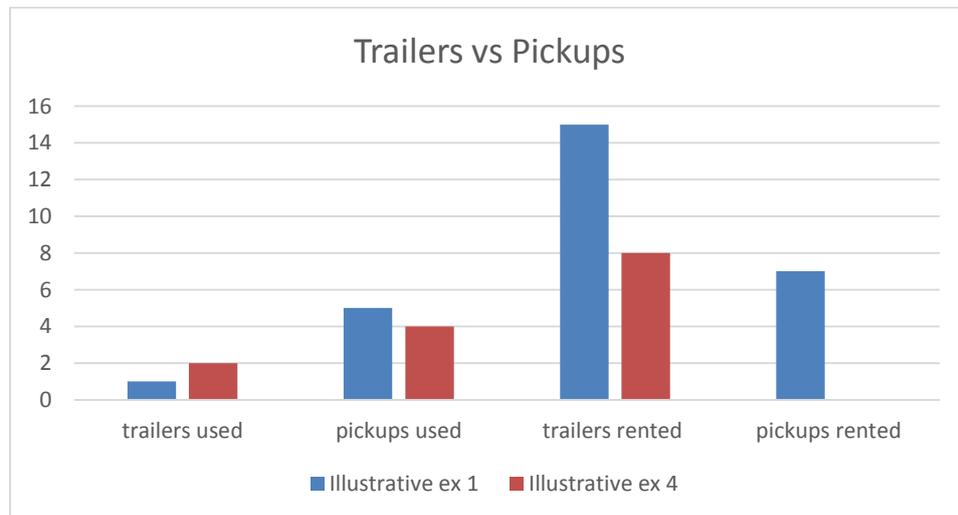**Figure 10: Study on number of trailers and pickups**
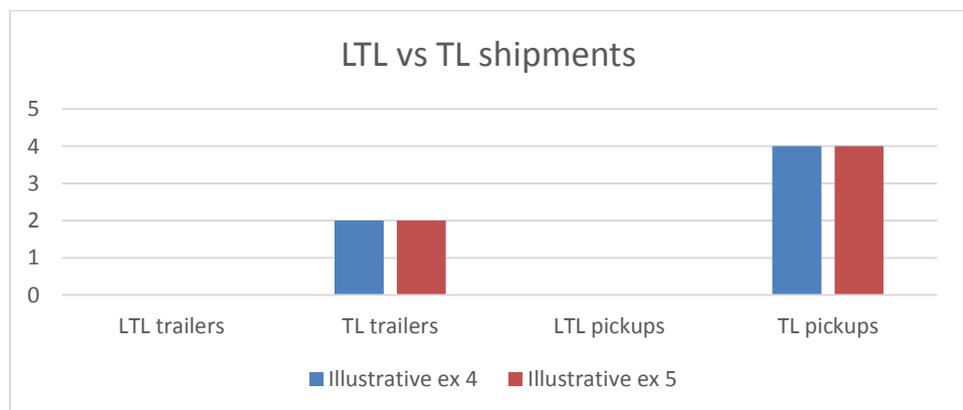
Figure 11: Study on number of TL and LTL shipments

The third study was conducted between the case that has alternative truck types for all echelons and a lead time of 1 time period for direct shipments (illustrative example 1), and the case using specific truck types for each echelon and

having a lead time of 1 time period for direct shipments (illustrative example 4). The cost of transporting goods for illustrative example 4 is greater and this could perhaps be due to the limitation of a specific truck type to each echelon (see Figure 12). There are no pickups rented in example 4 as it has just a few pickups allotted to echelon *jk*, and hence utilizes all its pickups. Looking at the LTL vs. TL results, it is better to have the option of having more pickups, considering low demand values at different retailers. This allows the consolidation of the goods at the cross-docks and helps in minimizing the transportation costs. The revenue generated in illustrative example 1 is much higher than that generated in illustrative example 4. This may be due to the fact that there are alternative truck types available, which have a higher renting cost for their transportation. In both cases, we have no LTL trailers or LTL pickups as the demand is very low (see Figures 13 and 14). The case tries to efficiently use all its trucks and hence there is maximum usage of TL trailers and pickups.

Figure 12: Cost comparison study of illustrative examples 1 and 4

Figure 13: Study on number of trailers and pickups

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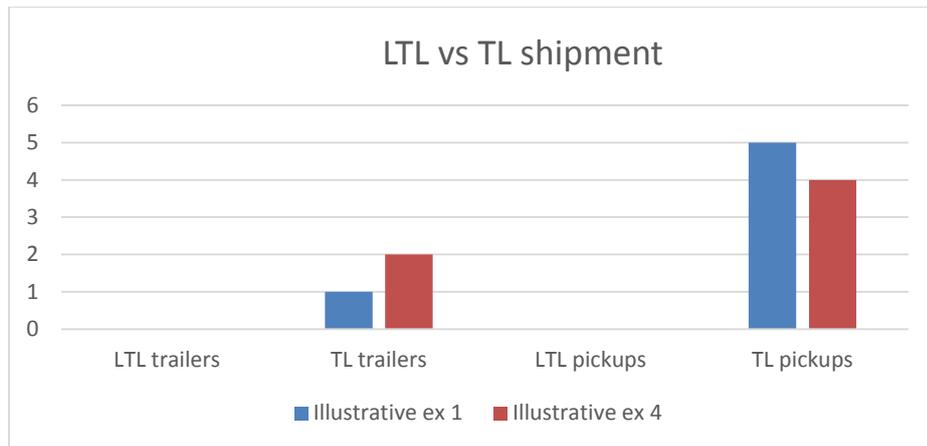
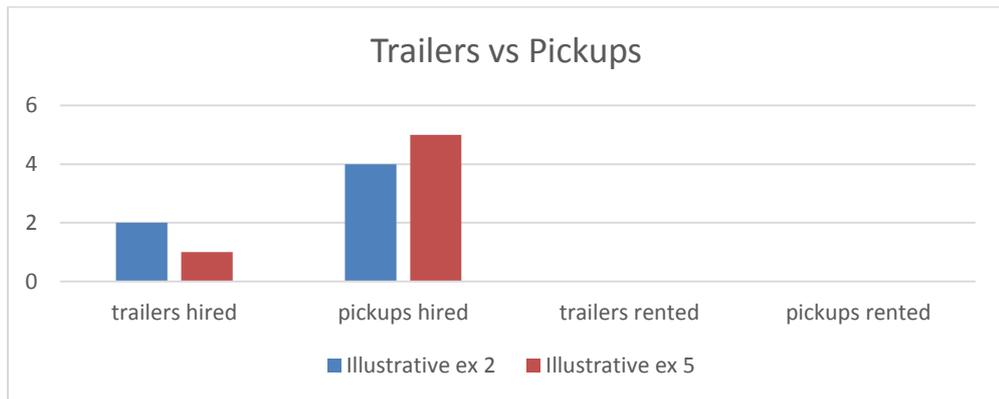**Figure 14: Study on the number of LTL and TL shipments**

The fourth study was conducted between the case that has alternative truck types for all echelons with a lead time of 1 time period for direct shipments and assuming no trucks are owned (illustrative example 2), and the case that uses specific truck types for each echelon with a lead time of 1 time period for direct shipments and assuming no trucks are owned (illustrative example 5). The cost of transporting goods for illustrative example 5 is greater than that for illustrative example 2 (see Figure 15).
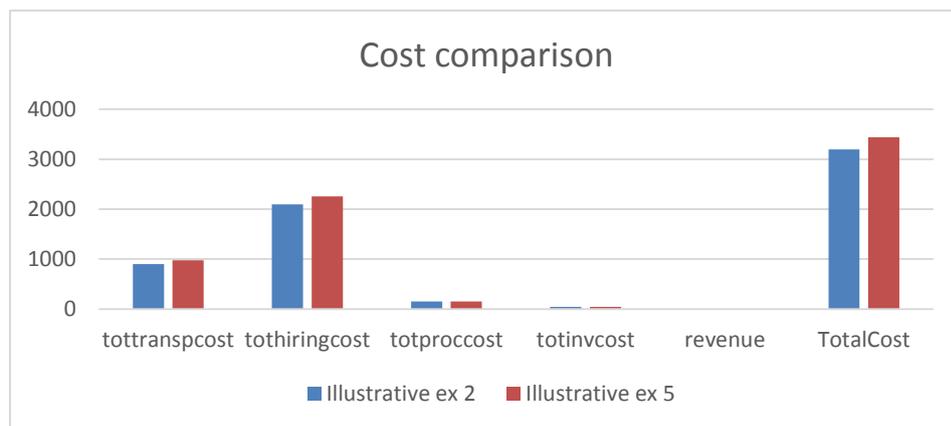
Figure 15: Cost comparison study of illustrative examples 2 and 5

This high cost is attributed to the higher costs of transportation using leased trailers. The leasing cost is higher for illustrative example 5 because of the limited availability of multiple truck types in each echelon. Both cases assume no trucks owned and hence there are no trucks rented to market, thereby generating no revenue. As seen from the Figures 16 and 17, more pickups than trailers are leased in illustrative example 5, due to the limited choice available. Looking at the LTL vs TL results, in both cases we have no LTL trailers and LTL pickups as the demand is very

low. The case tries to efficiently use all its trucks and hence there is maximum usage of TL trailers and pickups.

Figure 16: Study on the number of trailers and pickups
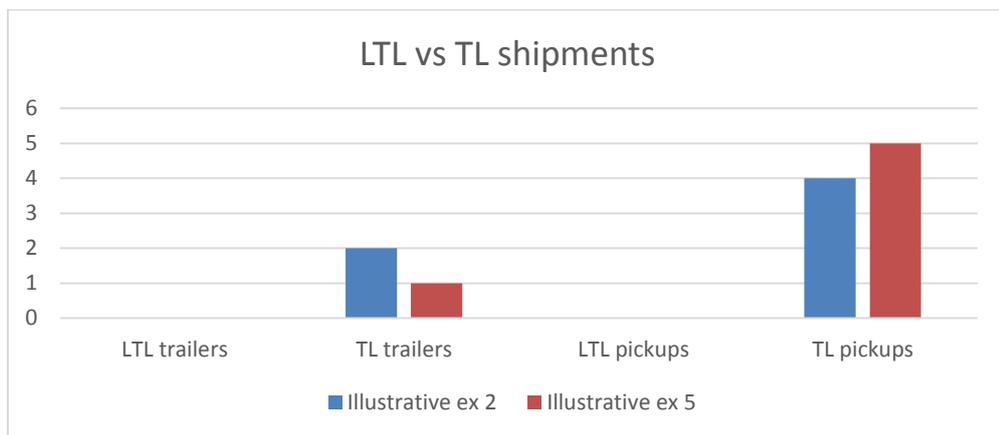
Figure 17: Study on the number of LTL and TL shipments

In the following computational analysis, the case that considers alternative truck type to each echelon with a lead time of 1 time period for direct shipments and assuming no trucks are owned is considered as the base case to assess the key problem parameters in the model's output. It is more realistic to assume having alternative truck types, as it brings down the transportation cost due to the availability of different truck types to cater towards varying demand. The retailer concentrates on its core competencies. It is also observed from the analysis that there is an impact on the leasing costs. The leasing costs are lower as compared to the other examples due to the availability of different truck types. In this case, the pickups cost less than the trailers.

Chapter 4: Computational Analysis

In this section, we perform a sensitivity analysis to test the effect of varying the key input problem parameters on the performance of the proposed model's outputs. As discussed earlier, the illustrative example with alternative truck types for each echelon, lead time greater than zero and no trucks owned is taken into consideration with all the basic parameter values remaining the same.

The various sensitivity parameters that are taken into consideration for the analysis are the change in demand, the change in inventory holding cost, and change in leasing cost. The performance of the model along with the changes in the mentioned sensitivity parameters is studied using the following measures: total cost structure, total number of trucks used for transportation, the percentage of trucks used for direct shipment, the percentage of trucks used for indirect shipment, total number of trucks with TL and LTL shipment, total inventory that goes through the cross-dock, total number of items processed at the cross-dock, the percentage of inventory over cross-dock-processed items, percentage of directly shipped quantity over demand, percentage of total inventory over demand, and the percentage of cross-dock-processed items over demand. Each scenario is run 10 times in the GAMS platform in CPLEX optimization software and then the average of each of those above-mentioned performance measures is taken into consideration to study the effect on the performance of the model. The various scenarios are discussed in detail in Table 18.

Table 18: List of all the sensitivity parameters and the different performance measures

Scenario#	Inventory holding cost	Demand	Leasing cost	Time taken to run scenario once
1	L [$1.36]	L [0-100]	M [Trailer: $485, Pickup: $322]	2 seconds
2	L [$1.36]	M [100-500]	M [Trailer: $485, Pickup: $322]	48 seconds
3	L [$1.36]	H [500-1000]	M [Trailer: $485, Pickup: $322]	16 minutes

4	M [$4.08]	L [0-100]	M [Trailer: $485, Pickup: $322]	2.6 seconds
5	M [$4.08]	M [100-500]	M [Trailer: $485, Pickup: $322]	24 seconds
6	M [$4.08]	H [500-1000]	M [Trailer: $485, Pickup: $322]	13 minutes
7	H [$8.10]	L [0-100]	M [Trailer: $485, Pickup: $322]	2.8 seconds
8	H [$8.10]	M [100-500]	M [Trailer: $485, Pickup: $322]	24 seconds
9	H [$8.10]	H [500-1000]	M [Trailer: $485, Pickup: $322]	4.2 minutes
10	M [$4.08]	M [100-500]	L [$130] for pickup only	15 seconds
11	M [$4.08]	M [100-500]	M [$220] for pickup only	36 seconds
12	M [$4.08]	M [100-500]	H [$322] for pickup only	5.6 minutes
13	M [$4.08]	M [100-500]	L[Trailer: $240 Pickup: $160]	12 seconds
14	M [$4.08]	M [100-500]	M [Trailer: $485 Pickup: $322]	39 seconds
15	M [$4.08]	M [100-500]	H [Trailer: $970 Pickup: $644]	1.6 minutes

4.1 Effect of changes in inventory holding cost vs changes in demand

In this section, we study the effect of the change in inventory holding cost on the performance measures of the model while having low, medium and high demands, respectively.

4.1.1 Scenario 1 vs. Scenario 2 vs. Scenario 3. The following results were obtained after running 10 iterations for each of the scenarios. On average, scenario 1 resulted in 98.46% shipments of products 1 and 2 getting processed through the cross-docks. Out of these total processed items for products 1 and 2, 51.06% of the inventory was stocked at the capacitated warehouse and shipped the following day. Less of product 3 was processed and stored at the warehouse. This may be attributed

to the fact that it has a higher volumetric weight as compared to the other products and hence most of it is shipped directly using TL pickups, and also because it has a high demand. Only 3% of product 1 is shipped directly and there was no direct shipment for product 2. These products were mostly processed through the cross-docks considering a low inventory holding cost for those items. This resulted in the consolidation of the products at the cross-docks. The indirect shipments through arcs ij were mostly using TL pickups and the ones through arcs jk were using TL pickups and trailers. A total of 5 trailers and 3 pickups were used for the transportation of products. The total average cost is around $5000. The average cost breakdown is shown in Figure 18. The processing cost is slightly higher, as 96% of the items are processed at the cross-dock.
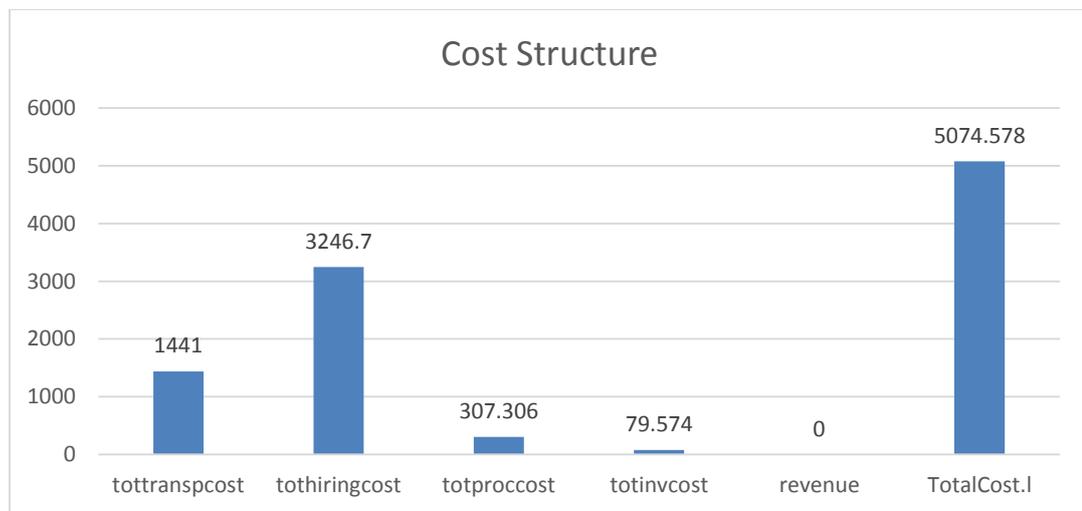
Figure 18: Cost structure for scenario 1

On average, scenario 2 resulted in around 45% of the direct shipments for all products. This shows that the remaining 55% of products were shipped indirectly. Out of these total processed items, there was more inventory for product 1 as compared to product 2 and 3 together, with the inventory over cross-dock-processed ratio at around 9% and 6%, respectively. This may be due to the fact that the volumetric weight of product 1 is smaller as compared to the other two products and therefore the priority is in shipping out products 2 and 3, as product 1 will occupy less space in the warehouse. The indirect shipments used around 12 trailers and 2 pickups and all of them had a full truckload (TL). This is basically 6 trailers through arcs ij and 6 through jk, and then 1 pickup each on arcs ij and jk, respectively. The total average cost is around $ 15,000. The cost breakdown is shown in Figure 19. The processing

cost is $1091 as only about 55% is processed through the cross-docks.
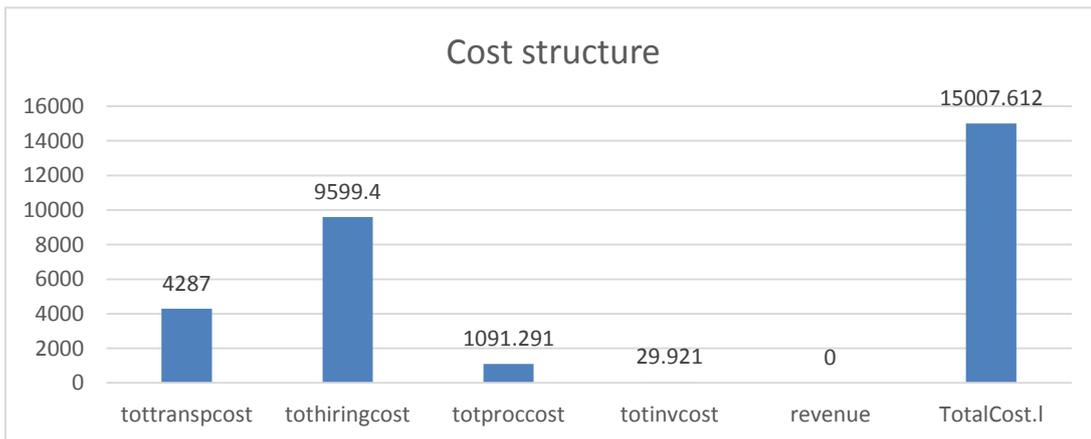
Figure 19: Cost structure for scenario 2

On average, scenario 3 resulted in around 47% of the direct shipments for all products. The rest of it was processed through the cross-docks. Out of these total processed items, there was more inventory for product 1 as compared to products 2 and 3 together, with the inventory over cross-dock-processed ratios at around 7% and 5%, respectively. Again this can be explained by the fact that the volumetric weight of product 1 is smaller as compared to the other two products and therefore the priority is in shipping out products 2 and 3. The indirect shipments used around 26 trailers and 2 pickups and all of them used full truckloads (TL). This is basically 13 trailers each through arcs *ij* and *jk*, and then 1 pickup each on arcs *ij* and *jk*, respectively. The total average cost is around $31,000. The cost breakdown is shown in Figure 20.
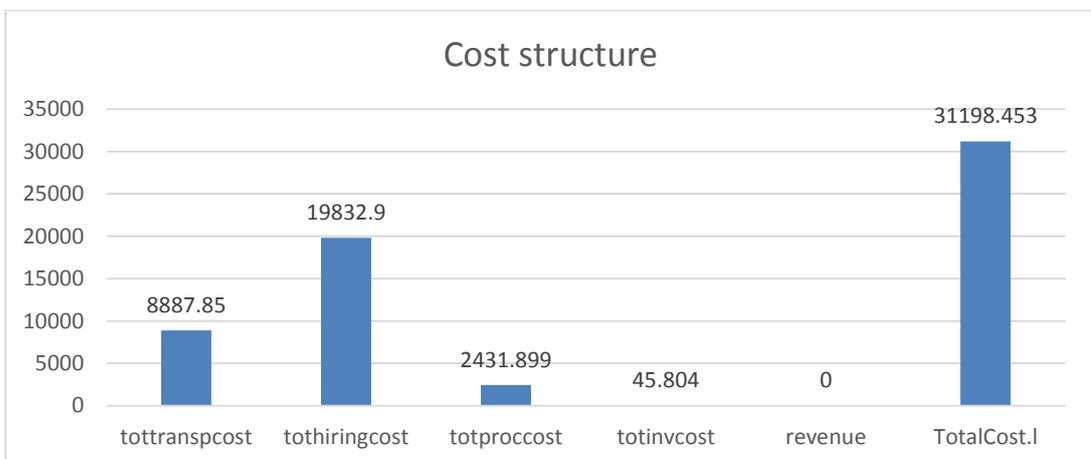
Figure 20: Cost structure for scenario 3

4.1.2 Scenario 4 vs. Scenario 5 vs. Scenario 6. The following results were obtained after running 10 iterations for each of the scenarios. On average, scenario 4

resulted in only around 12% of the direct shipments for all products, mainly using 1 TL trailer and 1 pickup. This is majorly affected by products 2 and 3, as only 6% of product 1 is shipped through directly. The remaining products are processed through the cross-docks. This may be due to low demands. Out of these total processed items, there was more inventory for product 1 and 2 together as compared to product 3, with inventory over cross-dock-processed ratio of around 42% and 31%, respectively. As the inventory costs increases, it is more economical to ship some products directly in order to minimize the inventory at the warehouse. The indirect shipments used around 5 trailers and 2 pickups, all of them being truckload (TL). This is basically 2 trailers through arcs ij and 3 trailers through arcs jk, and then 1 pickup each on arcs ij and jk, respectively. The total average cost is around $5233. The cost breakdown is shown in Figure 21.
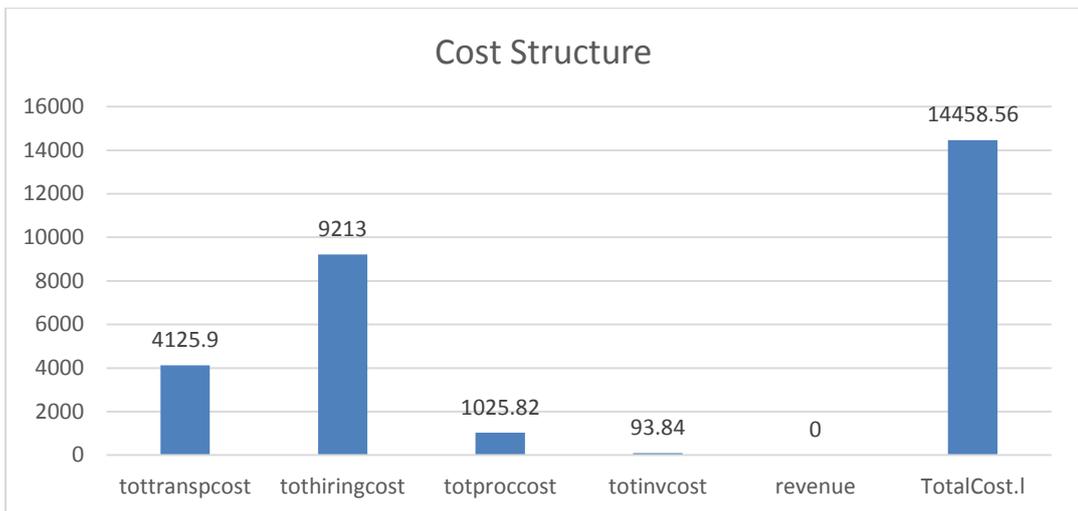
On average, scenario 5 resulted in around 45% of the direct shipments for all products, mainly using 6 TL trailers and 1 TL pickup. This is majorly affected by product 3, as only 50% of it is shipped through directly. The remaining products are processed through the cross-docks. In this case, product 3 has maximum demand as well, and due to the huge percentage shipped out directly, there is considerably less inventory at the warehouse. Thus, the inventory is now affected more by products 1 and 2, having around 13% and 7%, respectively. Out of the total demand, an average of 57.5% of products 1 and 2 are processed at the cross-dock. The indirect shipments used around 12 trailers and 1 pickup, and all of them, on average, were full truckload (TL). This is basically 6 trailers through arcs ij and 6 trailers through arcs jk, and then 1 pickup in arc jk, respectively. There were pickups used in arc ij too but they were very negligible with 10 iterations. Of the 10 iterations run, it was noticed in one of the runs that an LTL pickup was used in the jk echelon. This could possibly be used for small deliveries. The total average cost is around $14,458. The cost breakdown is shown in Figure 22.

On average, scenario 6 resulted in around 49% of the direct shipments for all products, mainly using 13 TL trailers and 1 and LTL and 1 TL pickup. This is affected by all products equally. The remaining products are processed through the cross-docks. However, due to rising inventory holding costs, the priority is in shipping out the products from the warehouse and hence this scenario results in around only 2% of inventory for all products combined.
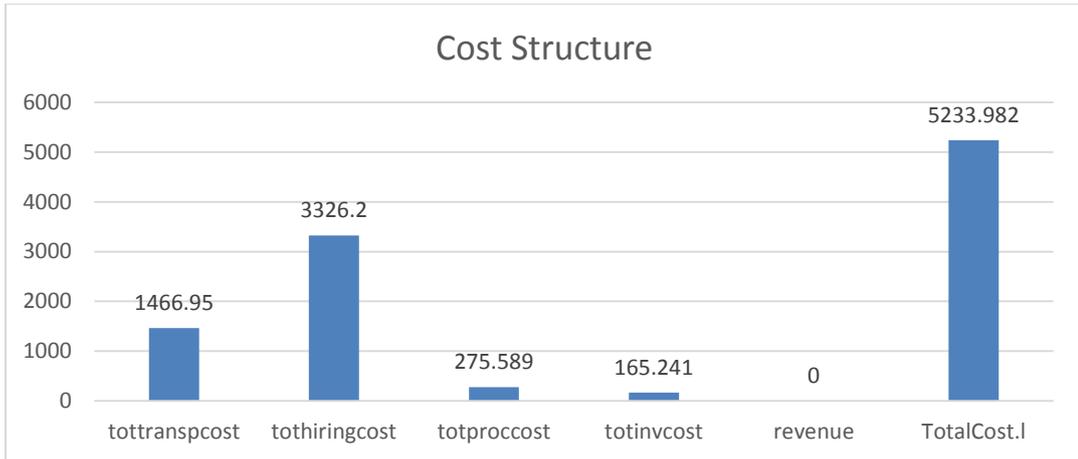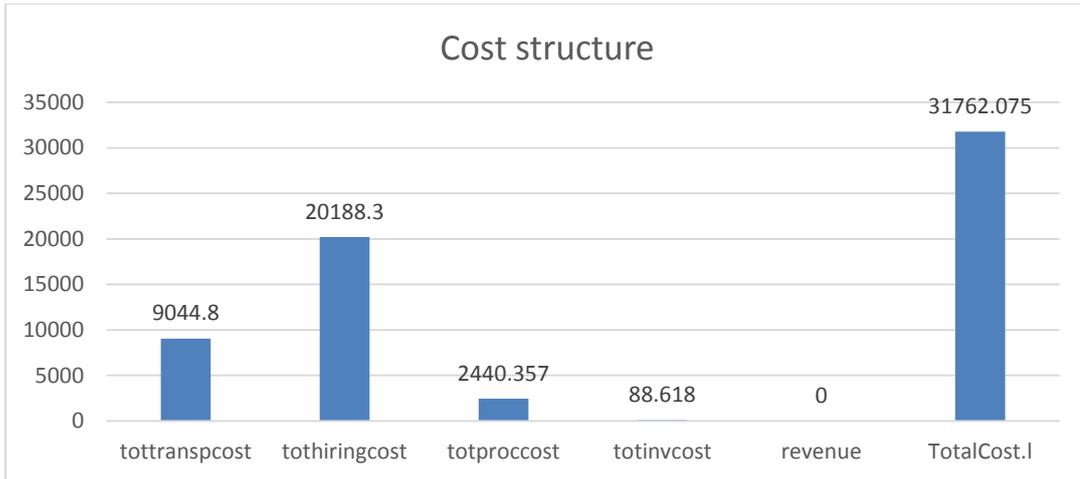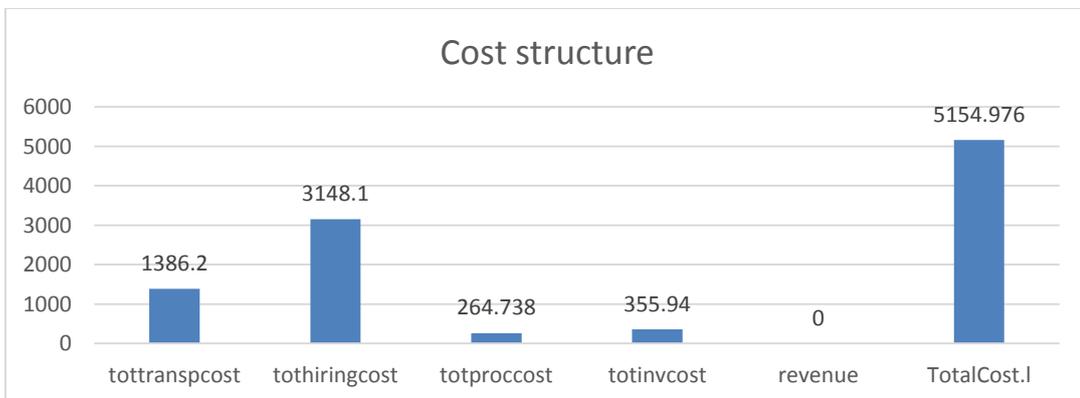
Figure 21: Cost structure for scenario 4

The indirect shipments used around 13 trailers and 2 pickups and all of them, on average, had full truckloads (TL). This is basically 6 trailers through arcs ij and 6 trailers through arcs jk, and then 1 pickup in arc jk, respectively. There were pickups used in arc ij too but they were very negligible with 10 iterations. However, the LTL pickup used in arc ij could mean that it would be consolidated with other goods from different suppliers at the cross-dock and then a full TL would be shipped out.

Figure 22: Cost structure for scenario 5

4.1.3 Scenario 7 vs. Scenario 8 vs. Scenario 9. The following results were obtained after running 10 iterations for each of the scenarios. On average, scenario 7 resulted in 96.4% of the shipments for products 1 and 2 getting processed through the cross-docks. Out of these total processed items, around 42% of the inventory was stocked at the capacitated warehouse and shipped the following day or week.
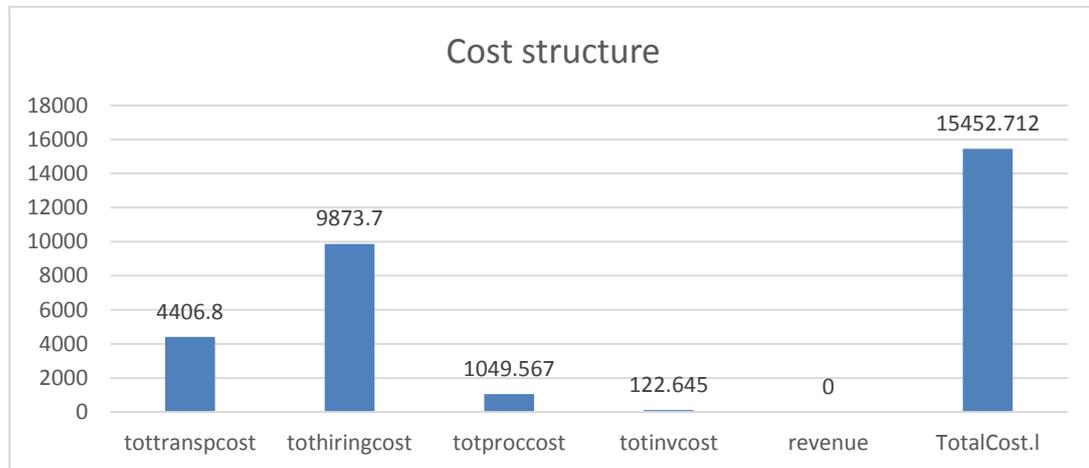
Figure 23: Cost structure for scenario 6

Less of product 3 is stored at the warehouse; this may be attributed to the fact that it has a higher volumetric weight as compared to the other products and hence most of it is shipped directly using a TL pickup and TL trailer. Due to the high inventory holding cost, the priority is to ship out product 3 as it results in high inventory costs compared to the other two. There were fewer direct shipments for products 1 and 2 due to a considerably low demand. The indirect shipments through arcs *ij* were mostly using 2 TL trailers and 1 TL pickup and the ones through arcs *jk* were using 2 TL pickups and 2 TL trailers. A total of 5 trailers and 4 pickups were used for the transportation of products. The total average cost was around $5154. The cost breakdown is shown Figure 24.

Figure 24: Cost structure for scenario 7

On average, scenario 8 resulted in around 48% of the direct shipments for all three products, mainly using 7 TL trailers and 2 TL pickups. This is affected by all products equally. The remaining products are processed through the cross-docks. However, due to rising inventory holding costs, there is very little inventory at the

capacitated warehouse. The smallest portion is 1.9% of inventory for product 3 out of the total 4%, as this is a high volumetric weight product. The indirect shipments used around 12 trailers and 2 pickups, and all of them, on average, had full truckloads (TL). This is basically 6 trailers through arcs ij and 6 trailers through arcs jk, and then 1 pickup each in arcs ij and jk, respectively. The total average cost is around $15,450. The cost breakdown is shown in Figure 25.

Figure 25: Cost structure for scenario 8

On average, scenario 9 resulted in around 49% of the direct shipments for all products, mainly using 13 TL trailers and 2 TL pickups. This is affected by all products more or less equally. The remaining products is processed through the cross-docks. In this case as well, due to the rising inventory holding costs and high demand for the products, there is no inventory stored for products 2 and 3, and very little inventory (about 1%) is stored at the warehouse. This means that products 2 and 3 are processed and shipped out the same day. The indirect shipments used around 26 trailers and 2 pickups and all of them, on average, were full truckload (TL). This is basically 13 trailers through arcs ij and 13 trailers through arcs jk, and then 1 pickup each in arcs ij and jk respectively. The total average cost is around $ 32,253. The cost breakdown is as shown in Figure 26.

4.1.4 Key insights from the analysis. This section describes the insights drawn from the analysis conducted on the three comparison scenarios mentioned above. Here, we focus on keeping inventory holding costs constant at low, medium and high, respectively. The related graphs are presented in Appendix A.
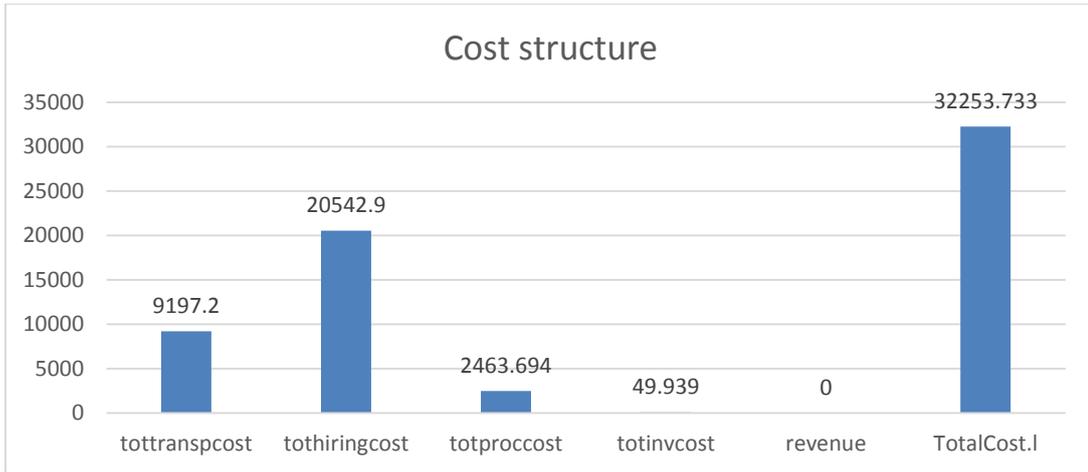
Figure 26: Cost structure for scenario 9

For low demands, it is observed that there are no direct shipments using trailers at all. All of the products are shipped through the cross-docks, and this is mainly done using pickups. However as the demand increases, there is an increased use of trailers for direct shipments, along with the many pickups used. But the number of trailers used for direct shipments is not as high as the number of pickups used, because the model tries to utilize more trailers for the indirect shipments.

As the demand increases, there is a tendency for more high volumetric weight products to be stored at the warehouse, if they are shipped via cross-docks. Hence the model tries to avoid this situation for high inventory costs by having direct movements and hence there is an overall decrease in the number of indirect shipments. There is a decrease in the number of items being processed at the cross-dock due to an increase in the number of direct shipments. This is also evident from the inventory to CD processed ratio, which shows an overall decrease in percentage with an increase in demand. The indirect shipments are mainly done using TL trailers as opposed to pickups. It is observed that there is a decrease in the use of pickups in echelon jk, as more of it is used in the direct shipments.

As the demand increases, it is observed that there is a decrease in the inventory to CD processed ratio. The model tries to ship out high volumetric weight products within a day in order to minimize having to store them, as it takes huge storage space at the warehouse. Therefore there is more direct shipment for such products and this allows for the storage of low volumetric weight products at the capitated warehouse. There are relatively high inventory levels for the low volumetric weight product 1 as compared to products 2 and 3 when the demand is low, but the

inventory tends to decrease for all items as the demand increases. The inventory is lowest for product 3 and highest for product 1.

4.1.5 Impacts of inventory costs at the three demand levels. This section describes the insights drawn from the analysis conducted to study the effect of varying inventory costs at the three demand levels.

The high volumetric weight goods occupy a lot of storage space at the warehouse, and this high volume contributes to high inventory costs as the inventory holding cost increases. So as to avoid the increasing inventory costs, the model tries to ship out most of the high volumetric weight inventory from the capacitated warehouse within the same day to different retailers. It is also noticed that a relatively small percentage of the high volume products as compared to the other products are processed at the cross-dock and a huge percentage is sent through direct shipments. The idea here is that, due to the limited storage area at the capacitated warehouse, the model tries to avoid a simultaneous situation where the warehouse is overstocked with products as well as a lot of products being processed at the cross-dock. Hence as the inventory costs increases, it ensures that the high volumetric weight goods are distributed via both direct and indirect shipments. For example, at low demand level, 100% of product 2 is being processed at the cross-dock and involves no direct shipment when the inventory holding cost is low. However, as the inventory costs increase, we can see a gradual decrease to around 85% of products being processed at the cross-dock, and the rest of around 15% being sent through direct shipment. Product 3 has 91% of its quantity processed at the cross-dock and around 9% shipped through directly when the holding costs are low. As the holding costs increases, the units processed at the cross-dock decrease to around 85%, and the direct shipment increases to around 15%. In all analyzed cases, major inventory at the cross-dock is affected by the low volumetric weight of product 1 and scarcity of product 2. This may be due to the minimal storage space occupied by the products. Therefore the model tries to retain the low inventory items at the capacitated warehouse and ship out the high volumetric weight inventory.

As the inventory holding costs increase, there is a need to ship the high volumetric weight products out of the warehouse immediately so as to reduce the total inventory costs. This is ensured by the model as it tries to increase the number of direct shipments. It utilizes more pickups for direct shipments. When we have low

demand, the model tries to use more pickups as it's more economical to send a full truckload of pickups instead of sending LTL trailers for low volumes. Hence in this case, there is an increase in the utilization of truckload (TL) pickups as compared to trailers for direct shipments. But for higher demands, there is an increased utilization of trailers to meet the demand requirements, as more pickups would be used in the indirect shipments and hence this is compensated by the usage of trailers. But it is definitely not as high as the usage of pickups for direct shipments. All the trailers and pickups used for direct shipping are truckload (TL) shipments.

The number of indirect shipments decreases slightly with the increase in inventory costs, considering an increase in the number of direct shipments. Indirect shipments mainly ship the low and medium inventory goods through the cross-dock. The model tries to use a greater number of trailers for indirect shipments (both arcs), as it tries to consolidate the products at the cross-dock and ship TL trailers to the retailers. There is, however, an increasing usage of TL pickups in arc *jk*. This perhaps could be attributed to the shipping of a truckload of only 1 product type targeted to a specific retailer. As the inventory holding costs increase, there is a need to lease more trucks to ship out the inventory from the warehouse and in this case, both echelons utilize more TL trailers compared to TL pickups.

The model leases more pickups for the direct shipments in order to bring down the total costs. As the inventory cost increases, fewer high volumetric weight products are being processed at the warehouse, and therefore this brings down the total processing costs. Both of these contribute to decreasing the total cost as the inventory cost increases.

4.2 Impacts of leasing costs at medium inventory and medium demand levels.

This section describes the insights drawn from the analysis conducted to study the effect of varying leasing costs at medium demand and medium inventory levels.

When the leasing cost for pickup is low, there are more direct shipments utilizing pickups as compared to trailers. But as leasing costs for pickups increases, there is a considerable decline in the use of pickups, from 74% to 41%, for the transportation of products through direct shipment. This is compensated by the increasing use of trailers for direct shipments. The model thus tries to optimize the use of pickups, as it is more economical to use a TL trailer by consolidating all products together rather than using many small pickups to ship the products. This results in less

volume that is transported through indirect shipments. There is a decreasing number of trailers used for indirect shipments, especially in echelon *jk*, and this allows for the consolidation of products at the cross-dock.

When the leasing costs for both pickup and trailer are low, there is more utilization of pickups as compared to trailers for direct shipments, considering the fact that pickups cost less than trailers. This is sufficient to meet the medium demand rate. But as the leasing cost increases for both the trailers and pickups, it is observed that there is a decrease in the use of pickups and an increase in the use of trailers for direct shipments. The model tries to optimize the use of pickups by sending full truckload trailers as opposed to many small pickups. But it is noticed that when the leasing costs for both truck types increase to a high value, once again the model tries to bring down the transportation costs by utilizing more pickups as compared to trailers, as each trailer costs around 1.5 times that of a pickup. This is compensated by the decreasing use of trailers for indirect shipments, and a small increase in its usage, when the leasing costs take a high value. The decrease in the use of pickups for direct shipments results in rerouting some of the volume through indirect shipments and this is done using the rest of the pickups especially for echelon *jk*, which is done by sending out full TL pickups.

Chapter 5: Conclusion

This research addressed the cross-docking problem, which is concerned with determining the best fleet dispatching and consolidation plans between supplier and retailer terminals using multiple truck types over a finite planning horizon. To the best of our knowledge, this research was the first to address the problem of optimizing the flow of multiple products between multiple supplier and retailer terminals taking complete advantage of a hybrid cross-docking facility. This cross-docking facility houses a small capacitated warehouse that is required for temporal storage of certain incoming goods. The developed supply chain model included the quantity-dependent transportation cost component in its objective function which hasn't been explored in the supply chain management literature. Thus the objective is to meet the retailers' demand with no delays by determining the load to be transported from origin to destination assuming that this load can come from different origins and be split and consolidated at the cross-docks before reaching the destinations. The developed model minimizes the total costs of transportation, throughput and inventory holding costs over the entire planning horizon. The model was formulated as a mixed integer linear program and was coded using CPLEX optimization software. The model can be used to determine the optimal transportation schedule for fleet dispatching using multiple truck types, whether using LTL or TL shipments, best consolidation plans at the cross-dock, and inventory storage decisions at the warehouse.

5.1 Research findings and key recommendations

It is observed that as the demand increases, there is an increase in the number of direct shipments using TL pickups. The model tries to avoid storing high volumetric weight items at the warehouse, which are responsible for high inventory costs, by having direct shipments. The indirect shipments are mainly carried out by TL trailers. Further, the increase in demand was found to have an effect on the processing costs. Since there is a decrease in the number of some of the medium and high volumetric weight items being processed at the cross-dock owing to an increase in the number of direct shipments, this results in decreasing the total processing cost at the cross-dock. However, there is a huge increase in the leasing costs as demand increases, as more trailers are leased for indirect shipments. It addition, it is observed that there is an overall decrease in the inventory to CD processed ratio, as the model

ensures the priority movements of high volumetric weight items in order to minimize their storage as it takes huge storage space at the warehouse. It is recommended that the retailer uses TL pickups for direct shipments as the demand increases, as each supplier offers specific product types and hence can consolidate all their products in one TL shipment. For indirect shipments, the facility could use trailers or pickups depending on the demand of the products required by the retailer. For lower volume products, the retailer could use pickups and for higher volumes he/she could use trailers. However, it is recommended that retailers' facility uses more TL trailers for shipments from cross-docks to retailers in order to allow for consolidation of goods from different suppliers. This ensures effective utilization of trucks and load space, as it could store more volume with more than one product type.

Further analysis was carried out to assess the impact of inventory costs at the three demand levels. As the inventory holding cost increases, it is noticed that a relatively small percentage of the high volumetric weight products as compared to the other products are processed at the cross-dock and a huge percentage is sent through direct shipments. This is attributed to the fact that these products occupy lot of storage space at the warehouse, and thereby contribute to high inventory costs. In all analyzed cases, major inventory at the cross-dock is affected by the low volumetric weight products, possibly due to the reduced space occupied by the products. It is also observed that there is an increase in the number of direct shipments as the inventory cost increases, which are mainly done utilizing TL pickups. This direct shipment is partially helped by the use of TL trailers as the demand increases. Consequently due to the increase in direct shipments, there is a decrease in the number of indirect shipments, which focuses on consolidating and shipping the medium and low volume products using TL trailers and a few TL pickups. Therefore it is recommended that the retailer aims at minimizing the storage of high volumetric weight products at the warehouse and aims to ship them out at the earliest as the inventory costs increases. It would be more economical to send the small percentage of high volumetric weight products from the cross-docks using a TL trailer than sending two small pickups. So the model strives to find the best tradeoff between high leasing costs and high inventory holding costs.

It is noticed that as the leasing costs for the pickups increases, there is a considerable decline in the use of pickups for the transportation of products through

direct shipment, which is compensated by the increasing use of trailers. It is more economical to use a TL trailer by consolidating all products together rather than using many small pickups to ship the products. The same pattern is followed when the hiring cost for both the trailers and pickups increases. However, it is noted that as the leasing costs increase to a high value, again more pickups are utilized for direct shipments as leasing a trailer is more costly than leasing a pickup. Hence these trailers would be compensated for indirect shipments at high leasing costs.

5.2 Limitations and Future Research

Whilst the findings of this study could be applied in most cases, there were some relevant exceptions. Firstly, the size of the network problem solved in this work is small which restricts the number of suppliers, cross-docks and retailers, over a small planning horizon. The lead time is considered to be non-negative and we consider the lead time only for direct shipments which is one time period. This was used to simplify the work of this study. But a better understanding can be achieved by studying non-zero lead times for all echelons. We considered a quantity-dependent transportation function in the objective function. Future research topics could expand the current study by increasing the size of the problem and expanding the number of suppliers, cross-docks, and retailers as well as the planning horizon. The development of heuristic procedures for large problems is another venue for future studies. Further, future research can also use other types of freight discounts, such as incremental and all-unit discounts.

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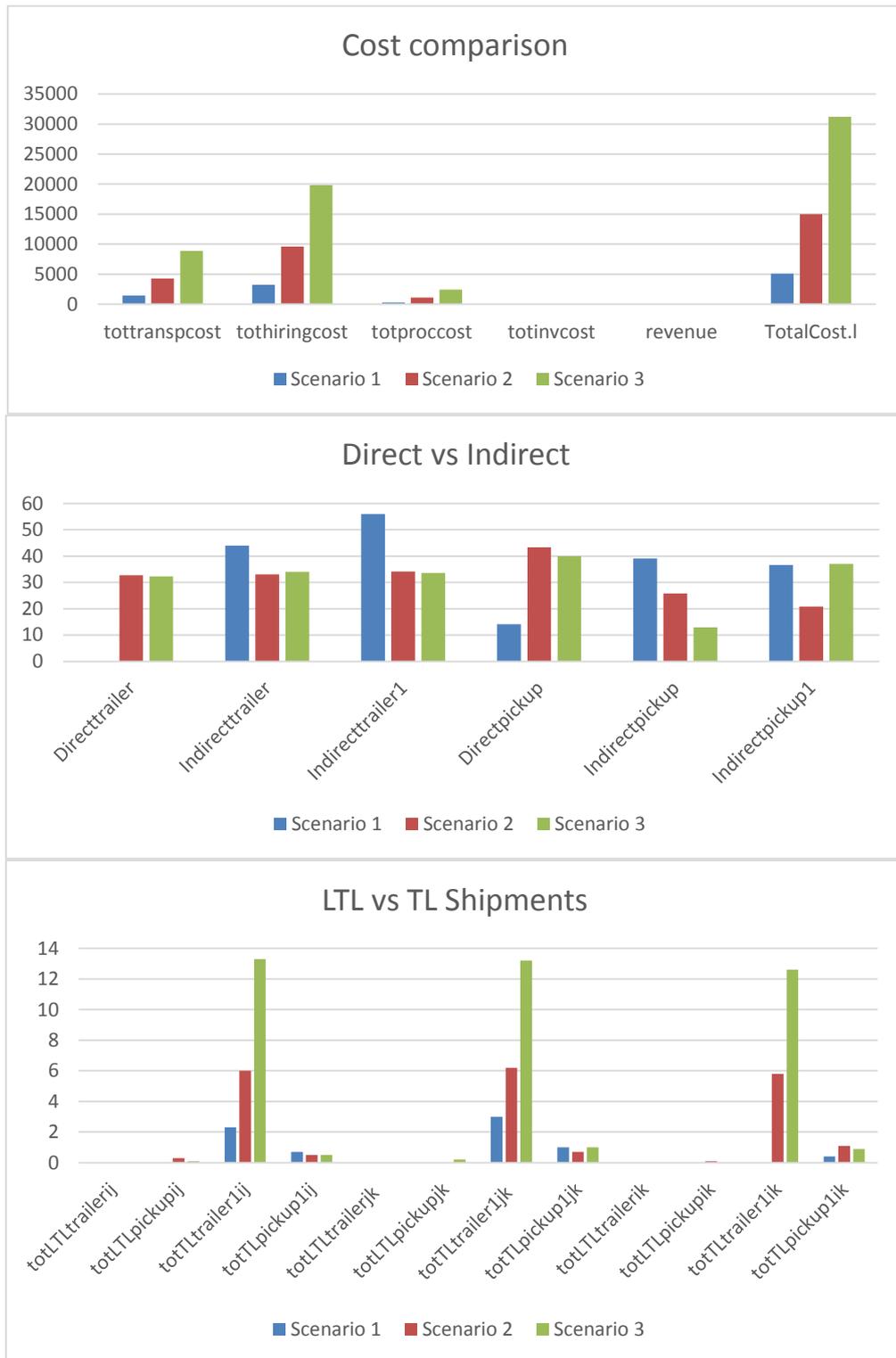
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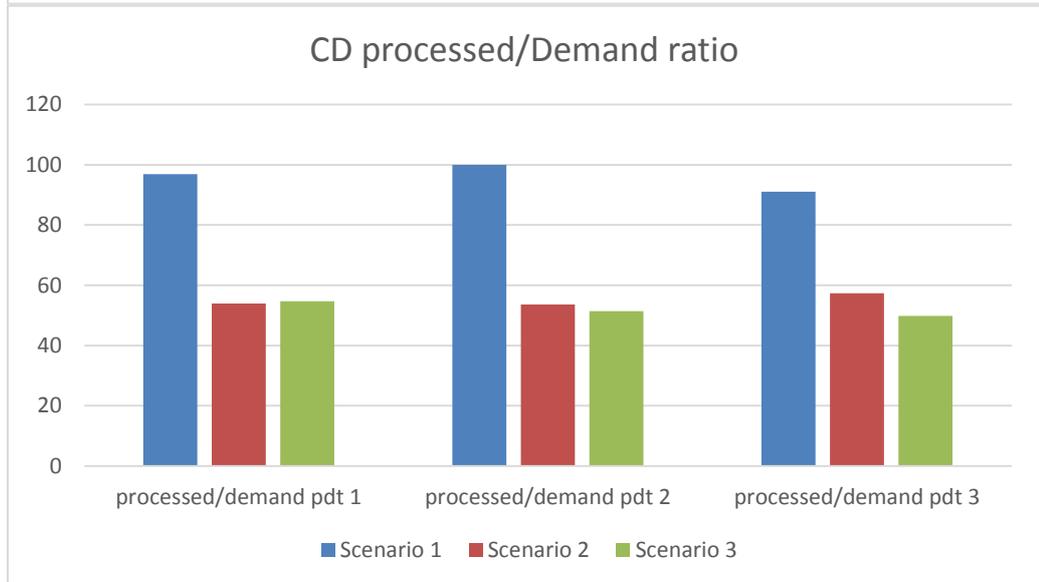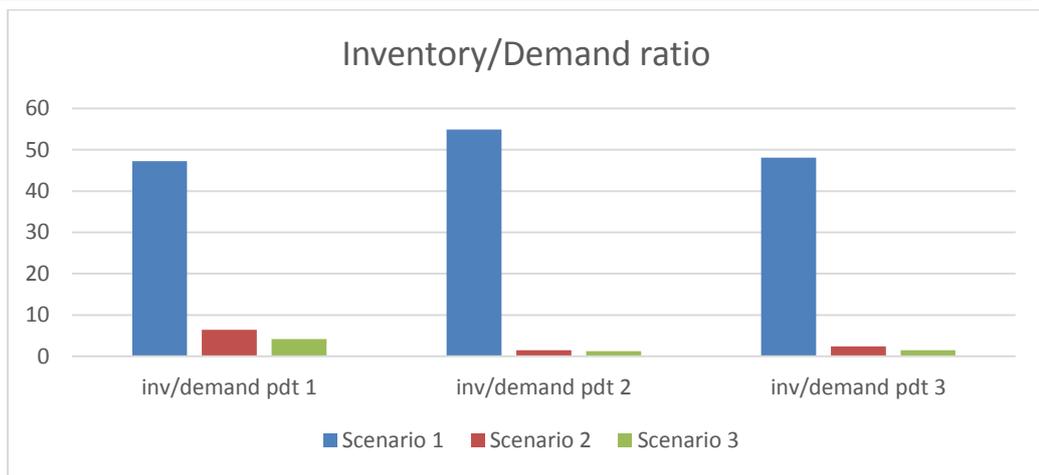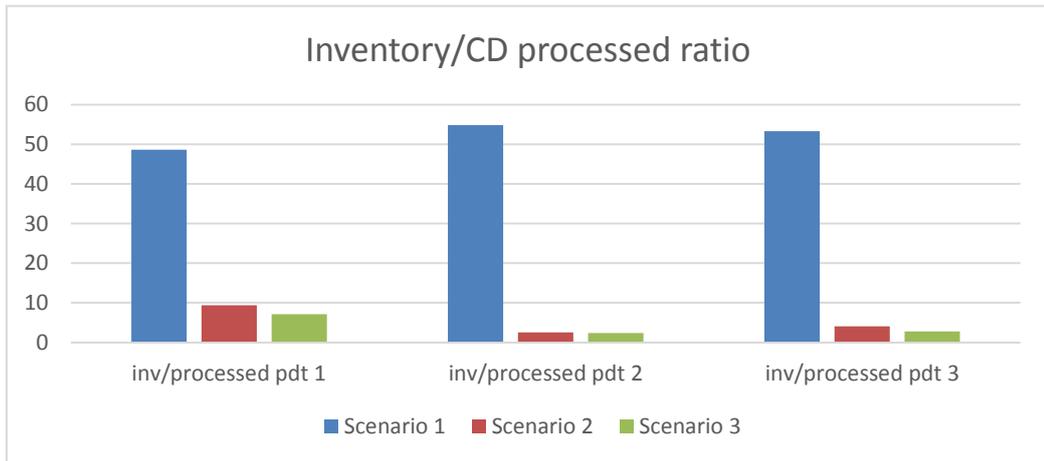
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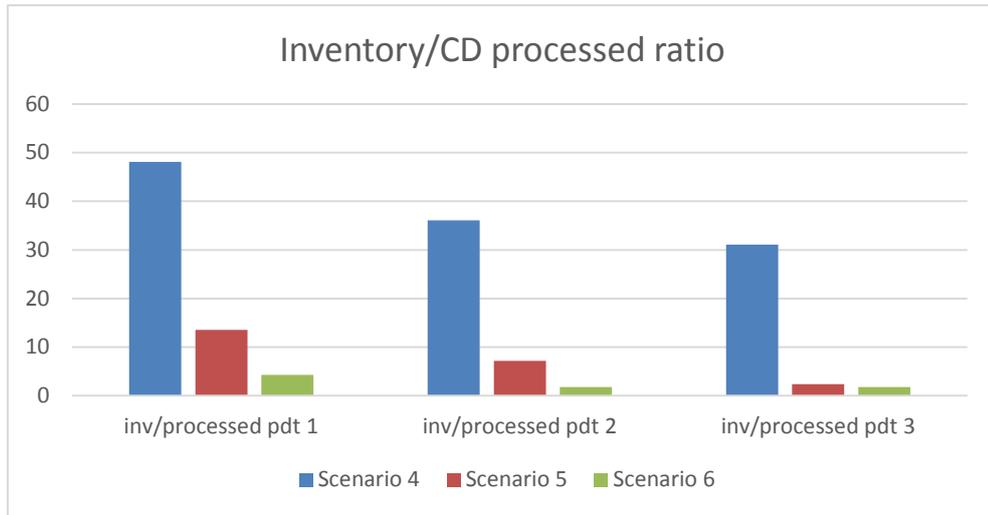
Appendix A

Study of the various sensitivity parameters with increasing demand values, at low inventory holding cost

Study of the various sensitivity parameters with increasing demand values, at low inventory holding cost

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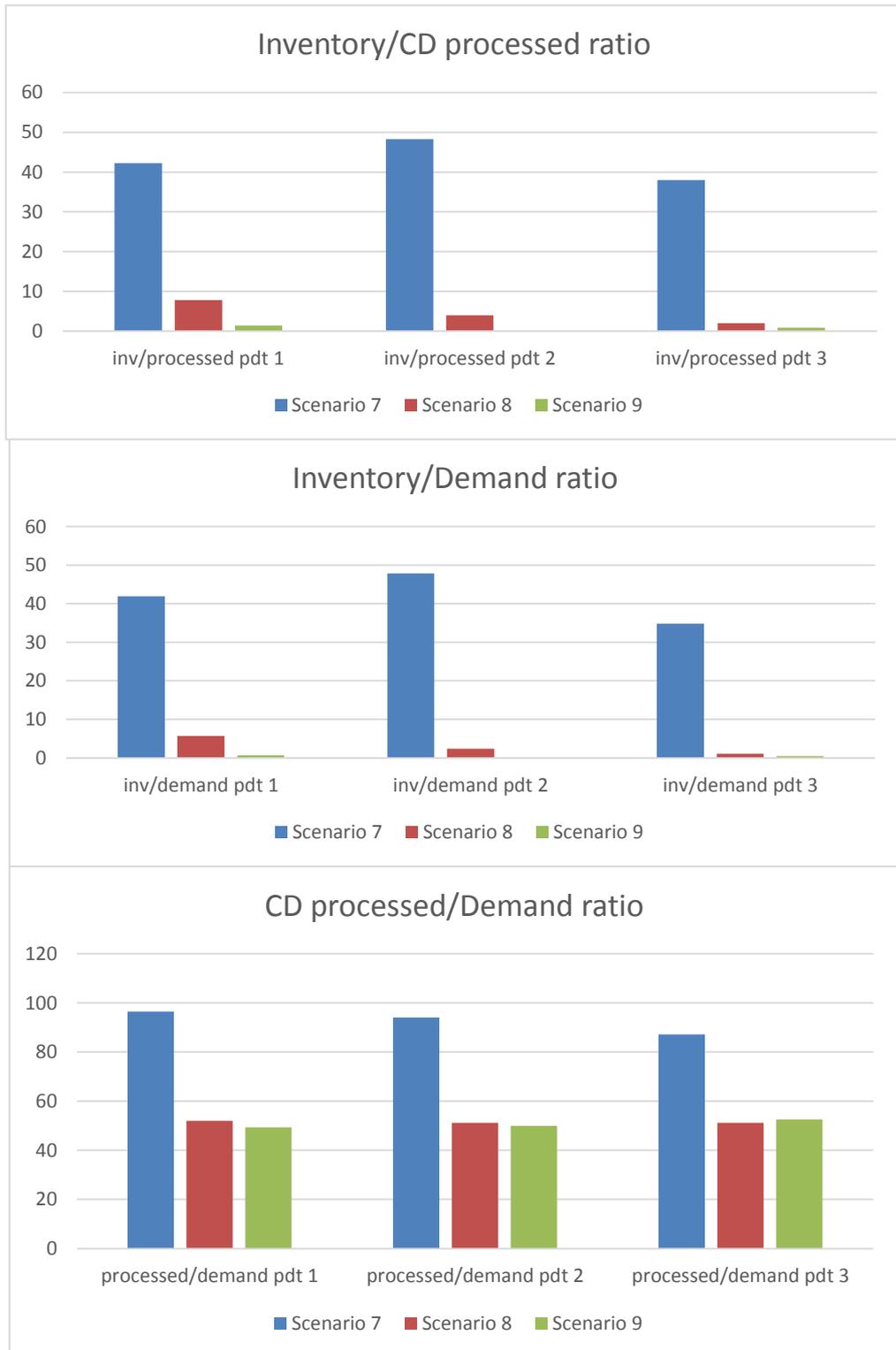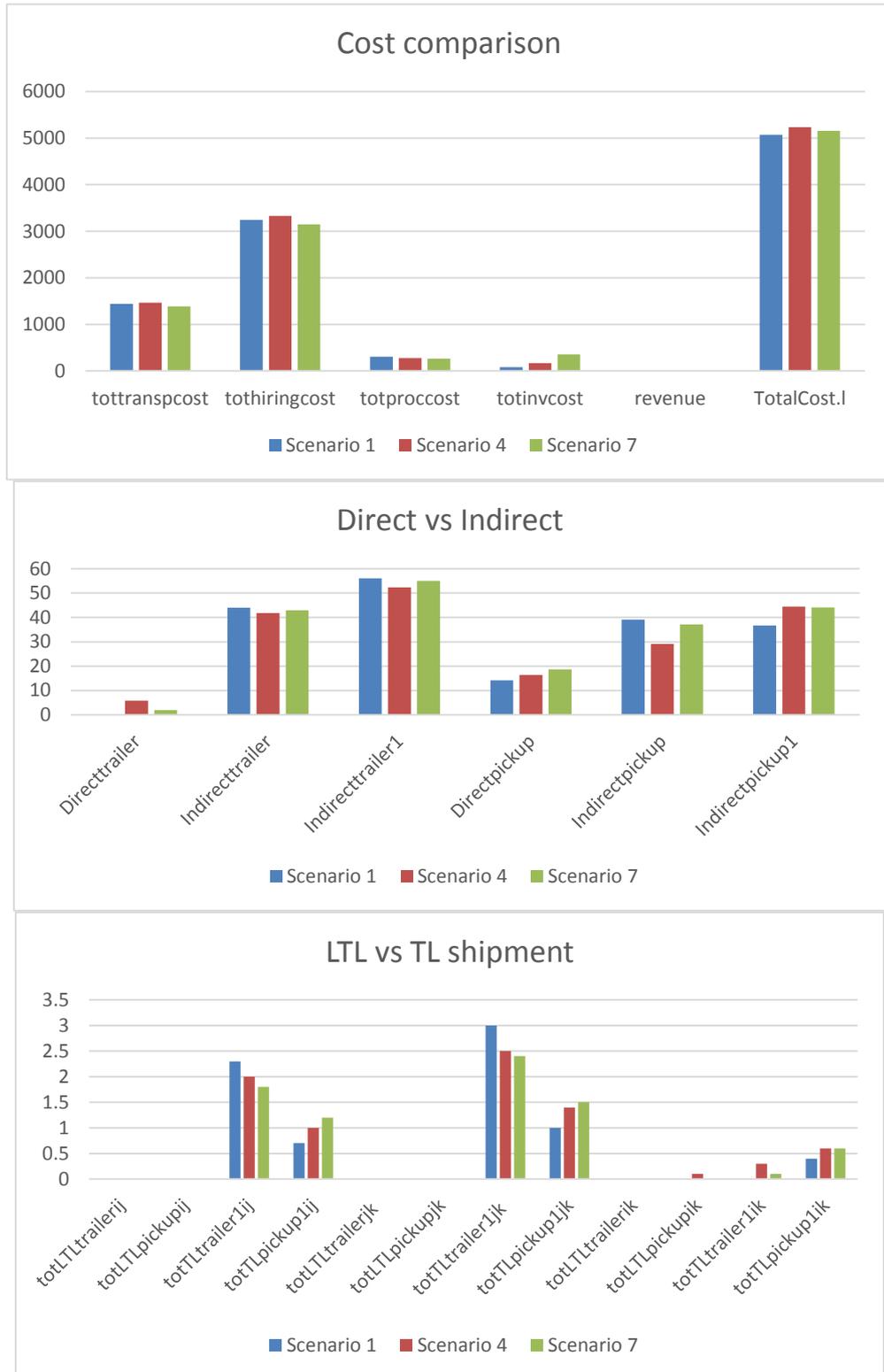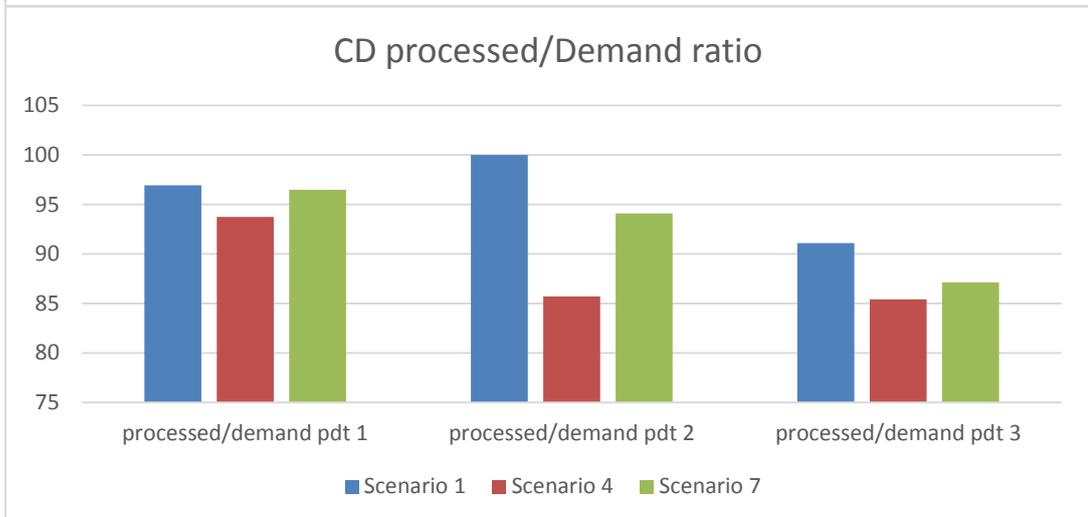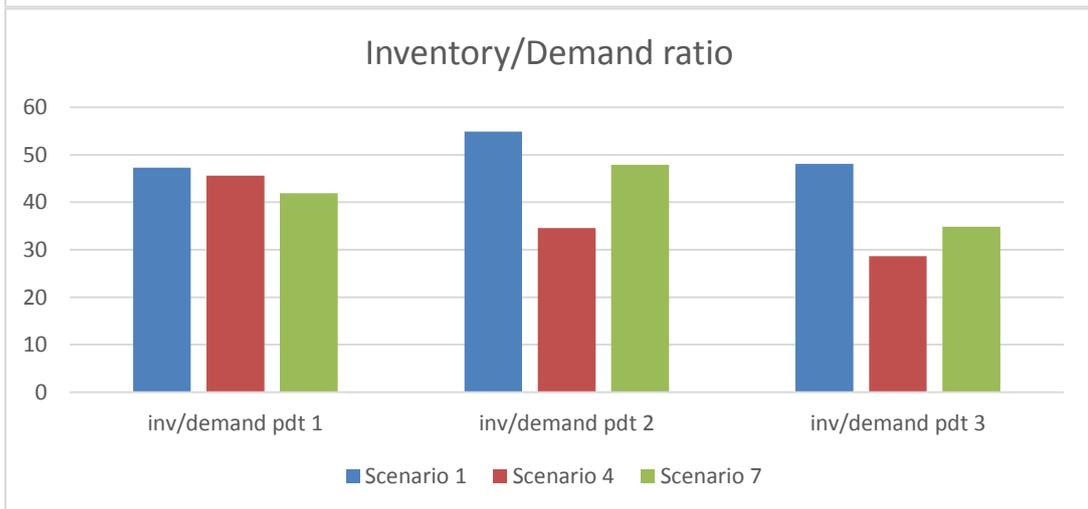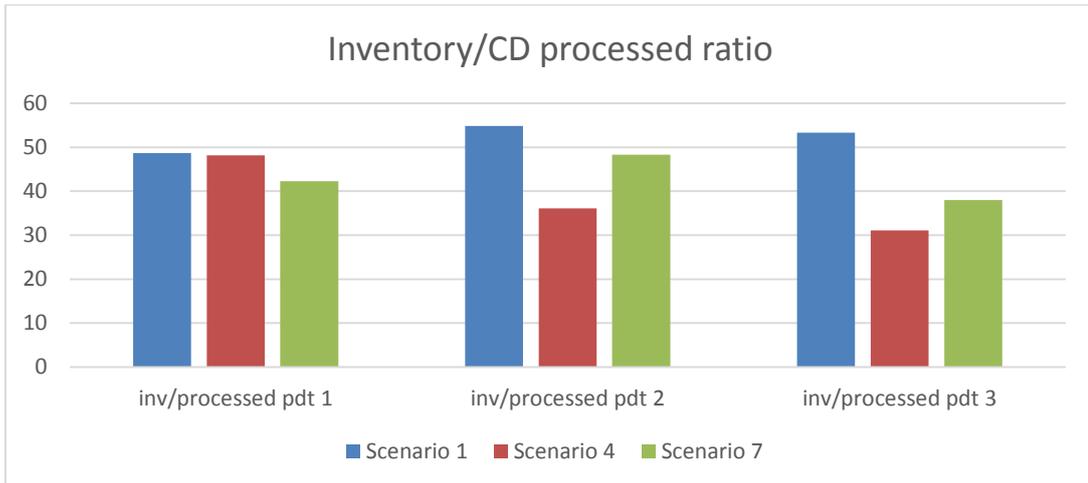**Study of the various sensitivity parameters with increasing demand values, at medium inventory holding cost**

Cost comparison

(Bar chart with categories: tottranspcost, tothiringcost, totproccost, totinvcost, revenue, TotalCost.l; legend: Scenario 4, Scenario 5, Scenario 6)

Direct vs Indirect

(Bar chart with categories: Directtrailer, Indirecttrailer, Indirecttrailer1, Directpickup, Indirectpickup, Indirectpickup1; legend: Scenario 4, Scenario 5, Scenario 6)

LTL vs TL shipment

(Bar chart with categories: totLTLtrailerij, totLTLpickupij, totTLtrailer1ij, totTLpickup1ij, totLTLtrailerjk, totLTLpickupjk, totTLtrailer1jk, totTLpickup1jk, totLTLtrailerik, totLTLpickupik, totTLtrailer1ik, totTLpickup1ik; legend: Scenario 4, Scenario 5, Scenario 6)

Study of the various sensitivity parameters with increasing demand values, at medium inventory holding cost

Study of the various sensitivity parameters with increasing demand values, at high inventory holding cost

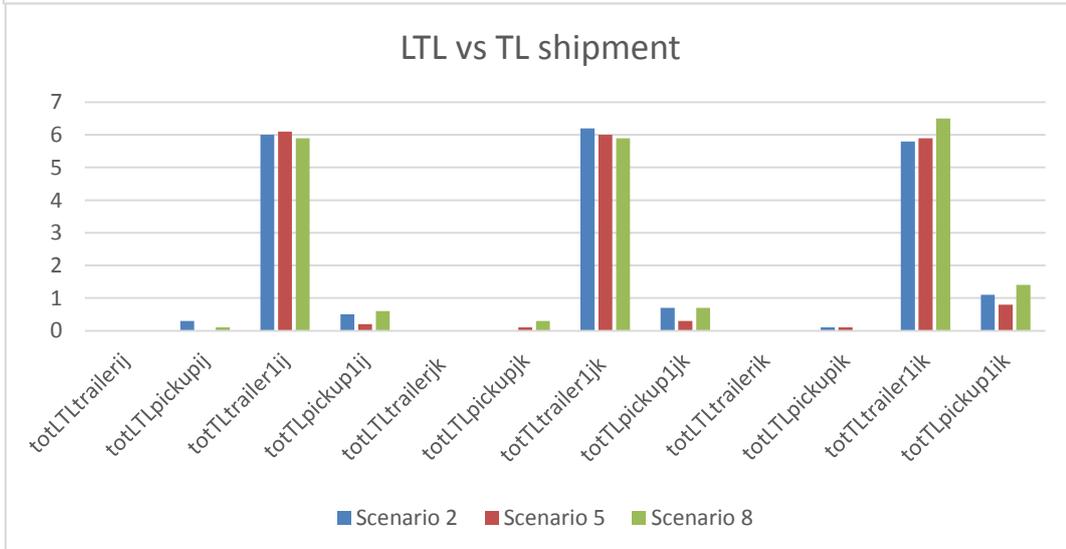**Study of the various sensitivity parameters with increasing demand values, at high inventory holding cost**

Inventory/CD processed ratio

Inventory/Demand ratio

CD processed/Demand ratio
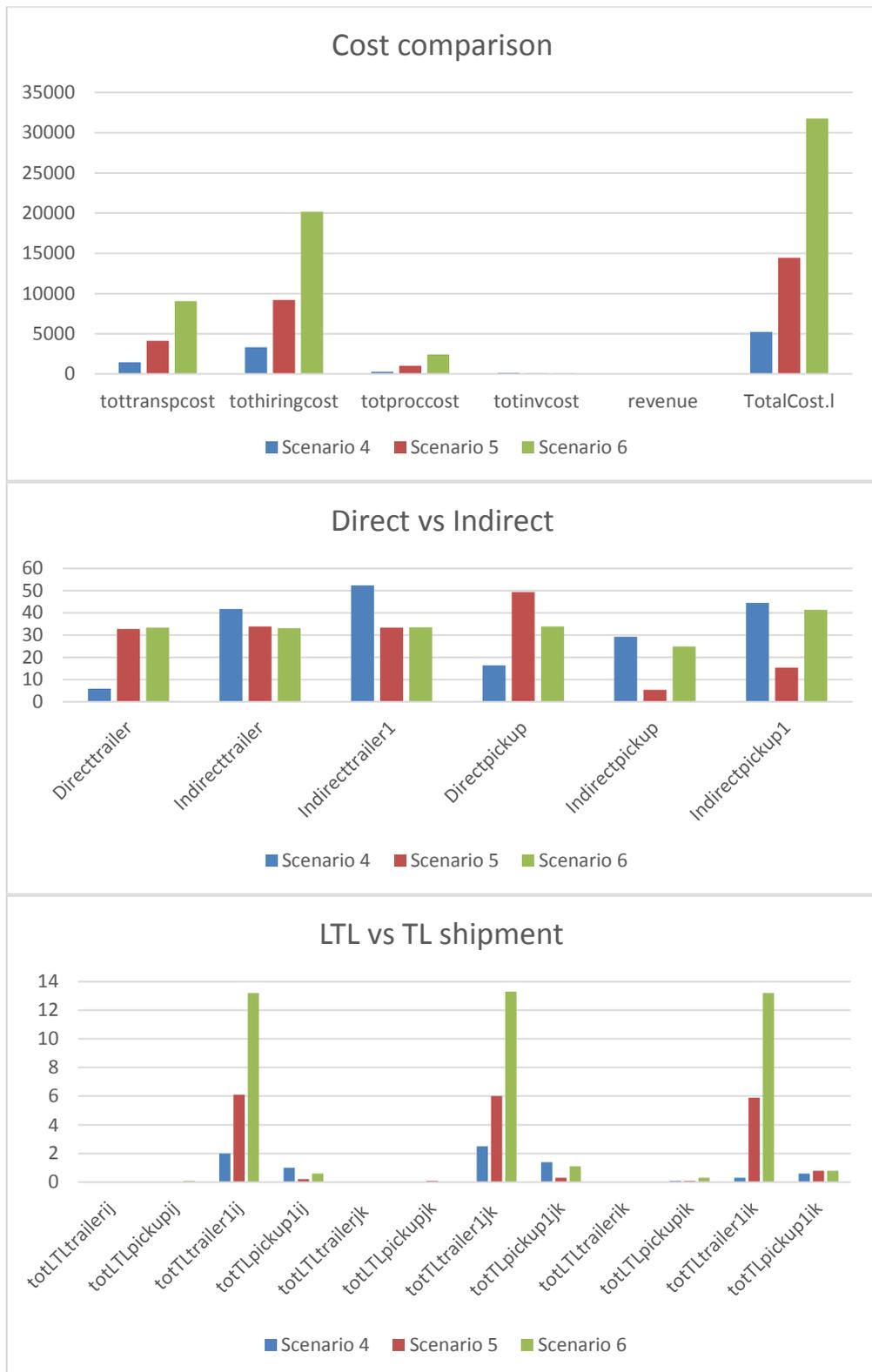
Appendix B

Study of the various sensitivity parameters with increasing inventory costs, at low demand values

Cost comparison

Direct vs Indirect

LTL vs TL shipment

Study of the various sensitivity parameters with increasing inventory costs, at low demand values

Inventory/CD processed ratio

Inventory/Demand ratio

CD processed/Demand ratio

Study of the various sensitivity parameters with increasing inventory costs, at medium demand values

Cost comparison

Direct vs Indirect

LTL vs TL shipment

Study of the various sensitivity parameters with increasing inventory costs, at medium demand values

Inventory/CD processed ratio

Scenario 2　　Scenario 5　　Scenario 8

Inventory/Demand ratio

Scenario 2　　Scenario 5　　Scenario 8

CD processed/Demand ratio


Scenario 2　　Scenario 5　　Scenario 8

Study of the various sensitivity parameters with increasing inventory costs, at high demand values

Cost comparison

Direct vs Indirect

LTL vs TL shipment

Study of the various sensitivity parameters with increasing inventory costs, at high demand values

Inventory/CD processed ratio


Inventory/Demand ratio

CD processsed/Demand ratio
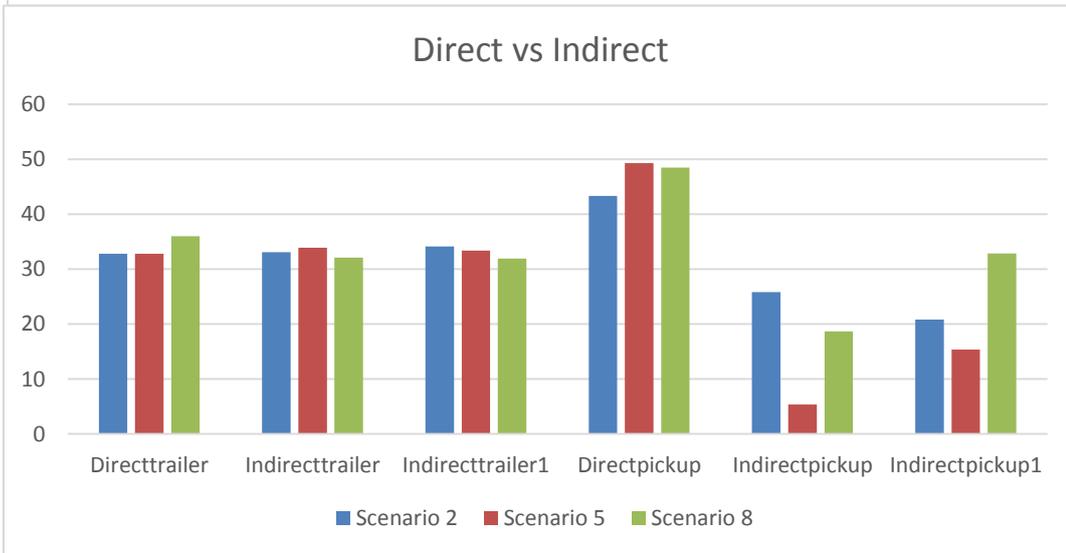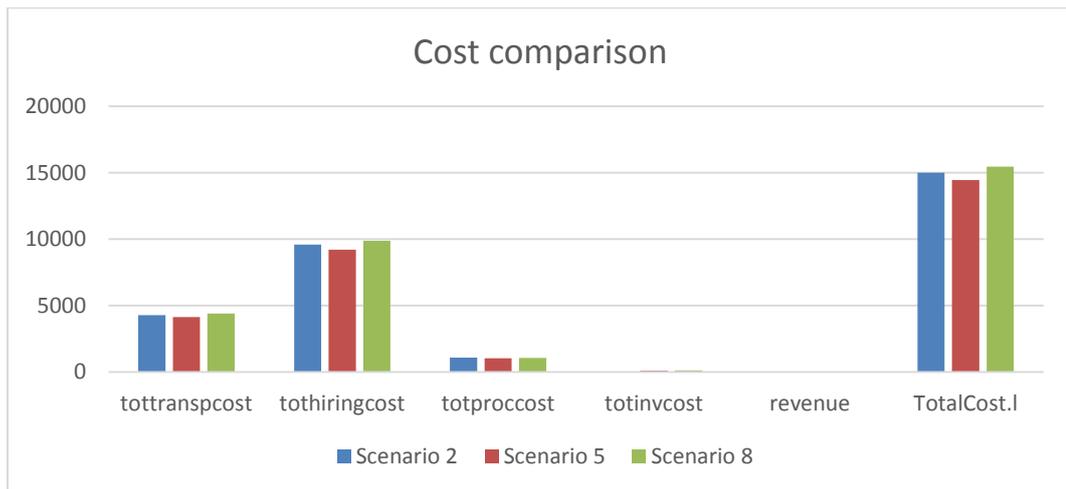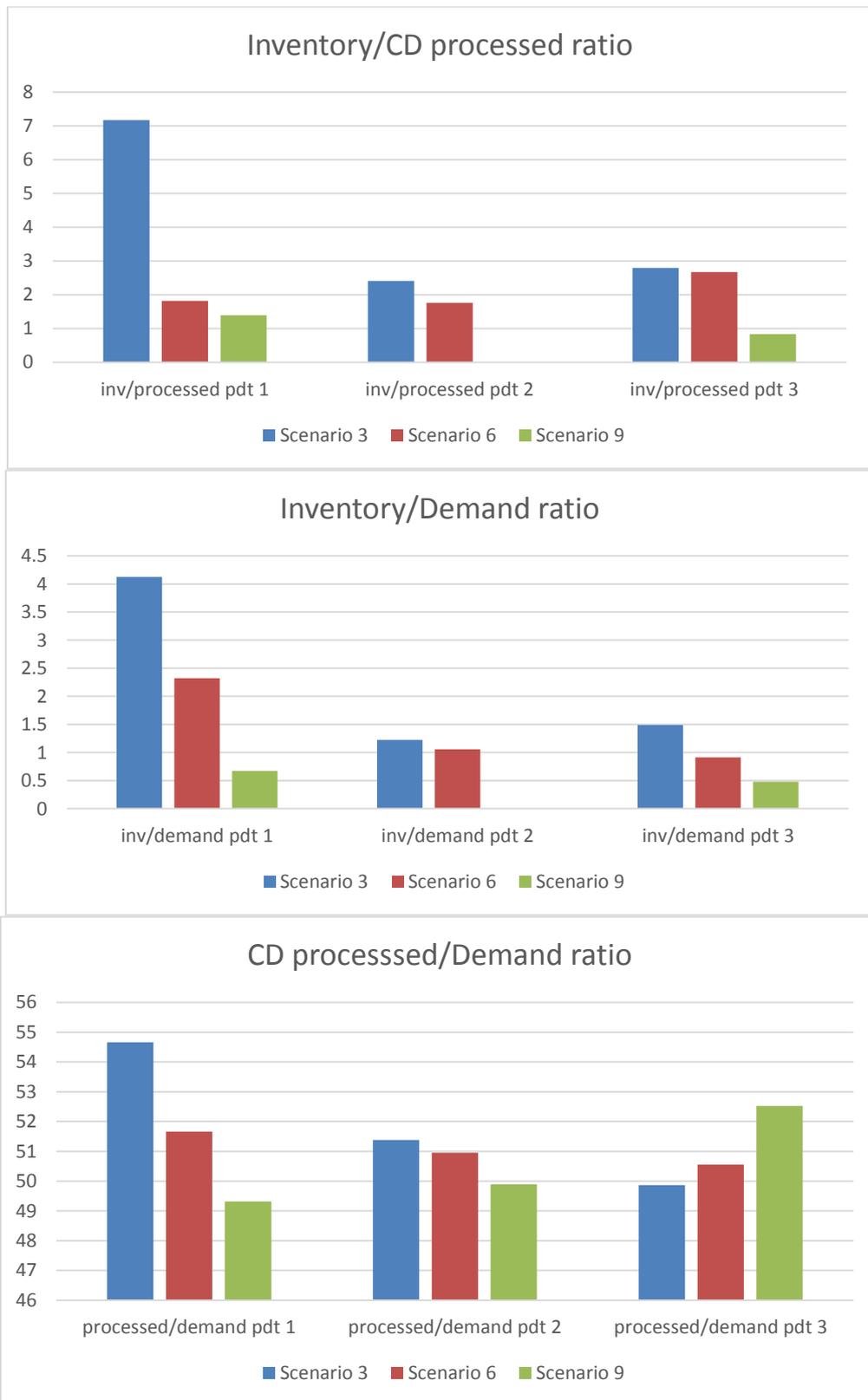
Appendix C
Study of the various sensitivity parameters with increasing leasing costs for pickups, at medium demand values and medium inventory costs

Cost comparison

Direct vs Indirect

LTL vs TL shipment
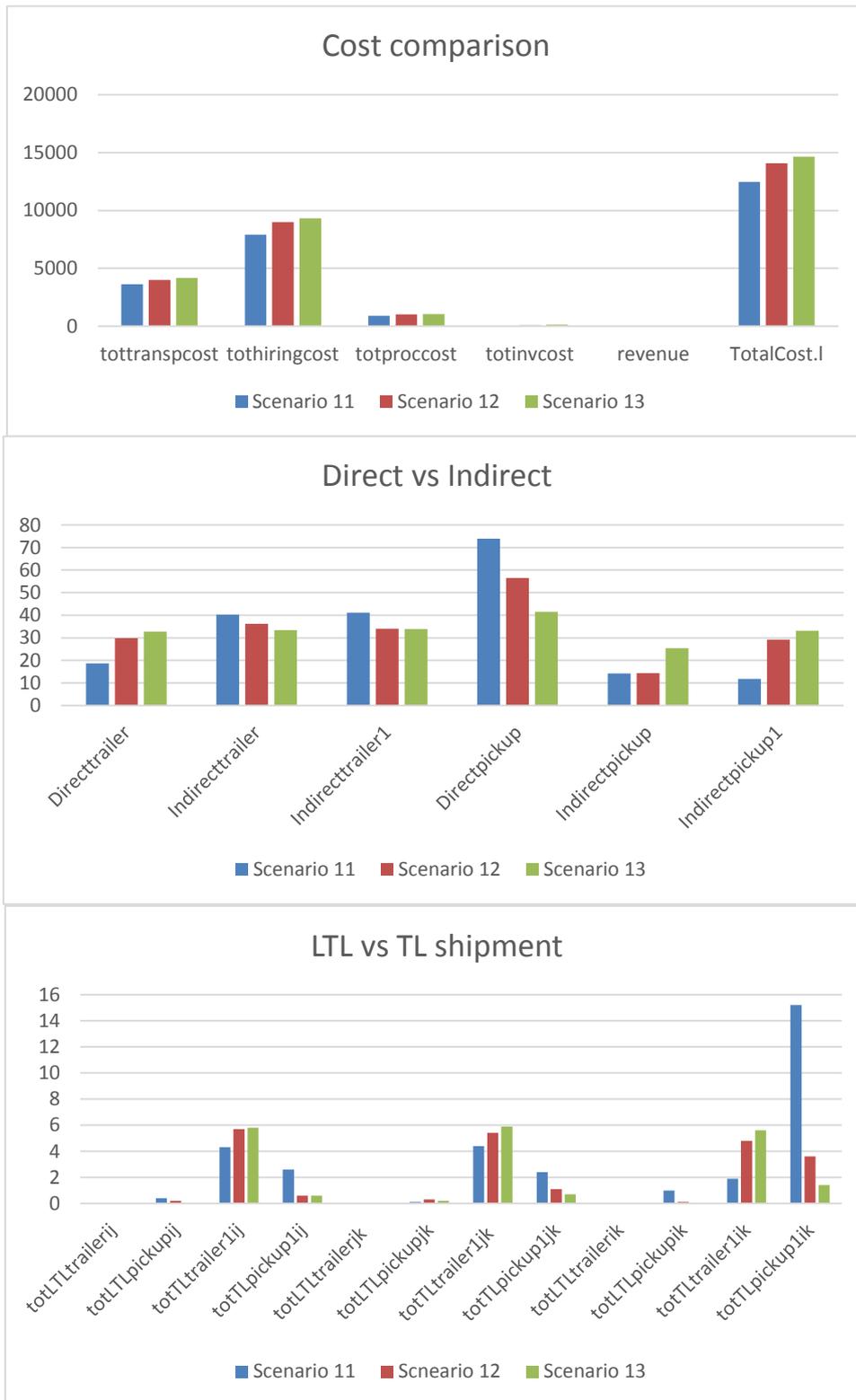
Study of the various sensitivity parameters with increasing leasing costs for pickups and trailers, at medium demand values and medium inventory costs

Cost comparison

Direct vs Indirect

LTL vs TL shipment
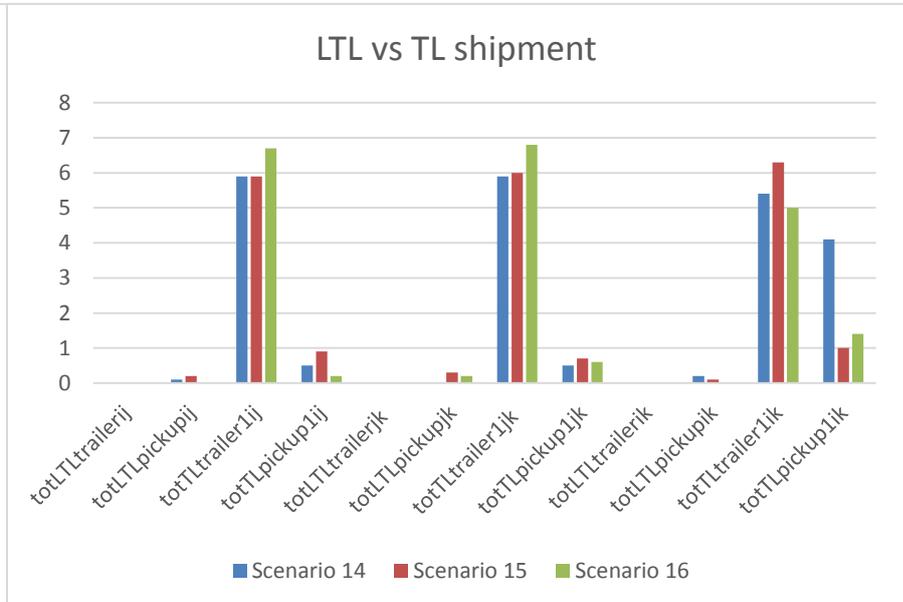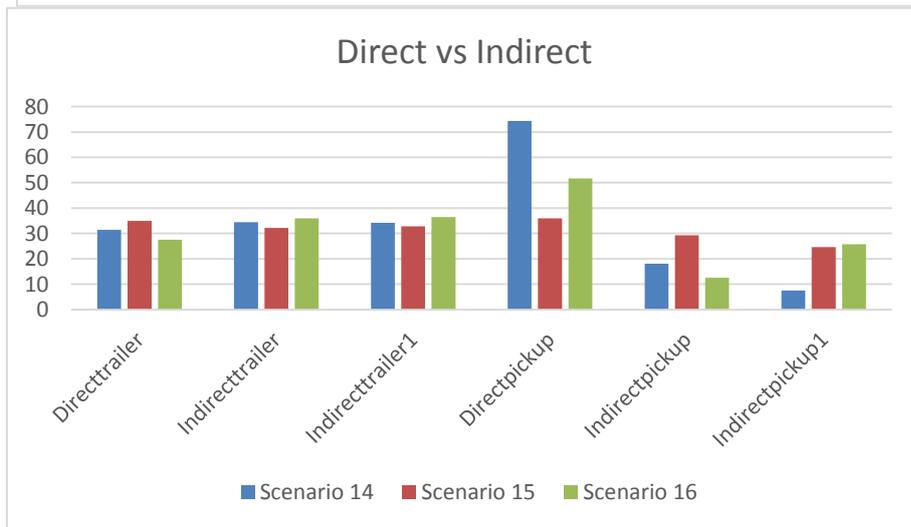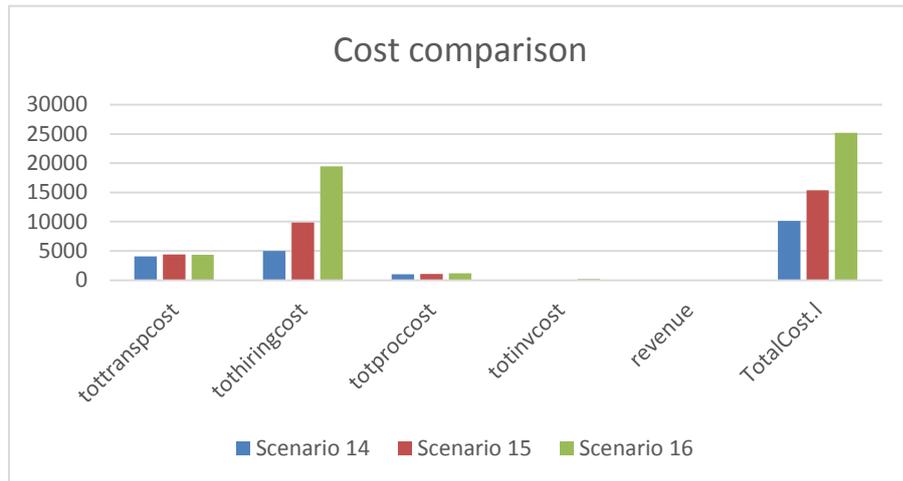
Vita

Ms. Sitara Holla was born in 1989, in Bangalore, Karnataka, in India. She was brought up in Sharjah, U.A.E. She was educated in local Indian schools and graduated from Sharjah Indian High School in 2006. She then graduated from Visvesvaraya Technological University, Bangalore, India, with a Bachelor of Science degree in Biotechnology.

After having worked in India as a quality control executive for a food-based company for a year, Ms. Holla moved back to the United Arab Emirates in 2011 where she began a Master's program in Engineering Systems Management at the American University of Sharjah. There she also worked as a graduate teaching and administrative assistant for two years at the Office of Graduate Engineering Programs. She then got recruited by L'Oréal and is currently working as a supply chain analyst for their Physical Distribution Department.