UC Berkeley

UC Berkeley Electronic Theses and Dissertations

Title

Optimizing a Retailer's Containerized Import Supply Chain

Permalink

https://escholarship.org/uc/item/9t01404x

Author

Davidson, Evan Taitz

Publication Date

2012

Peer reviewed|Thesis/dissertation

Optimizing a Retailer's Containerized Import Supply Chain

By

Evan Taitz Davidson

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering – Industrial Engineering and Operations Research

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Robert C. Leachman, Chair
Professor Carlos F. Daganzo
Professor Philip M. Kaminsky
Professor Zuo-Jun "Max" Shen

Fall 2012

Abstract

Optimizing a Retailer's Containerized Import Supply Chain

by

Evan Taitz Davidson

Doctor of Philosophy in Engineering – Industrial Engineering and Operations Research

University of California, Berkeley

Professor Robert C. Leachman, Chair

An economic optimization model of waterborne containerized imports from Asia to the USA for a retailer is described. The retailer's imports are allocated to alternative ports and logistics channels so as to minimize total transportation and inventory costs. Goods may be shipped via the logistics channel of direct shipment of marine containers via truck or rail to retail distribution centers, or via transportation to cross-docking facilities in the hinterlands of the ports of entry and trans-loading goods from marine containers into domestic trailers or containers. A previous model has been built for a retailer employing a single optimal importing strategy, specifying the allocation of each retail distribution center to its optimal port of entry and the choice of direct shipment or trans-loading, uniformly applied across the importer's entire product portfolio.

Here we describe a methodology to extend this model to allow for a retailer that can employ multiple optimal strategies, applied to different classes of goods within its product portfolio segmented by inventory holding cost rate. We find that for the retailer's cost minimization problem, it is provably optimal to generate sub-problems by splitting goods into consecutive valuation partitions. By doing so, the retailer's multi-strategy problem becomes computationally tractable. We examine the impact of less-than-container shipments on the optimal set of strategies. This allows us to more accurately estimate the transportation cost.

We collected data, including origin-destination transportation rates and lead times, from a top five national big-box retailer to test both single and multiple strategy methodologies. Using these parameters, we found that our case study retailer could potentially reduce their total supply chain cost by over 2.1% by using an optimal single strategy, and over 2.6% by using different optimal strategies for the various goods in their portfolio. We then examine the optimal single strategy and set of multiple strategies for retailers of various importing volumes and declared goods valuation distributions. The optimal single strategy for a retailer generally shows direct shipping for the lowest value goods and lowest demand volume retailers, trans-loading at three to four ports for slightly higher value of goods and demand volume, and trans-loading at fewer and fewer ports as the good value and volume continue increasing. For our tested parameter set, the cost reduction generated by allowing multiple strategies for a single retailer can further reduce the total supply chain cost by up to 1%.

Lastly, we analyze the value of building redundancy into the supply chain to mitigate the cost of disruptions. We note that many retailers utilize more ports than our model would recommend as optimal. We have found that there is value in a retailer always utilizing at least two ports of

entry to protect against supply chain disruptions at any single port. However, for those retailers whose optimal port usage already includes at least two ports, disruption mitigation would not provide enough benefit to justify the additional infrastructure investment. We hypothesize that there exist other factors such as institutional inertia and negotiation leverage that contribute to the use of these additional ports of entry.

Table of Contents

Acknowledgements

I would first and foremost like to thank Professor Robert Leachman. He has truly been a great teacher and mentor, and his guidance, support, and direction has made my graduate school career possible. I have learned so much from him, and I look forward to taking all of that into the future with me.

My dissertation committee, Professors Carlos Daganzo, Philip Kaminsky, and Max Shen, have been a huge help in making this dissertation to be all that it is. Their suggestions and guidance have been significantly useful in shaping this project. I would also like to thank Professors Candace Yano and Dorit Hochbaum. Their classes and seminars have provided me the tools to be a better researcher.

I would like to thank Professor Stephen Graves for his mentorship throughout my undergraduate career at the Massachusetts Institute of Technology. He helped me develop as a student and a researcher, and cemented my interest in the field of Operations Research.

I would like to thank my professional colleagues, most especially Ellen Nussbaum, Kaushik Katari, Ziad Nejmeldeen, and Rama Ramakrishnan. During my work at ProfitLogic and Oracle, they each acted as a mentor to me, and provided the encouragement to go back to school, apply myself, and learn more.

The Nagui Bagua crew, Dave, Ben, Alex, Scott, Liz, Colin, Julie, Sean, Sarah, John, and Jenna, have provided a much needed respite every summer. Each year they gave me the chance to clear my head and move forward in my research. I just hope that I live up to the sterling reputation of the great Dr. Ironbeard.

Most importantly, I would like to thank my parents Samuel and Shelley and my sisters Lesley and Alexandra. Their love and unwavering support throughout my life have made this all possible. They have always been there for me, never faltering when I needed help or encouragement, and always pushing me to be greater. Thank you.

1. Introduction

This dissertation proposes a shortest path optimization model for structuring the supply chains of large importers of waterborne containerized goods from Asia to USA. This optimization model determines the least-cost set of supply chain strategies for an importer, in terms of ports and landside transportation modes (channels) to be used for selected partitions of the importer's entire portfolio of imported merchandise. We then apply this cost minimization model to test against a case study retailer's current supply chain strategy, examine the breakpoints between different optimal strategies or sets of strategies, and analyze the effect of disruptions on a retailer's supply chain.

A typical large US importer/retailer operates Retail Distribution Centers (RDCs) that restock retail outlets. Differences in inventory costs resulting from use of alternative supply channels typically extend only as far as the RDCs, which are typically located within an overnight drive to the outlets they supply. In this dissertation, we consider the origins for import shipments to be factories in China and elsewhere in Asia, and the destinations to be RDCs spread across the Continental USA. While the portfolio of products for an importer may encompass multiple origins, typically any particular product is to be distributed across the Continental USA and is sourced from a single Asian origin.

Forty foot long marine containers from Asian origins are shipped on vessels to ports of entry (POE) to the USA, called "ports" in this dissertation. The containers may be assigned to their respective destination RDCs while at the still at the Asian origin and directly shipped inland after reaching the port, called "direct shipment," or they may be unloaded at trans-load or import warehouse facilities and the contents sorted and re-shipped in domestic vehicles to multiple RDCs, under a strategy termed "consolidation-deconsolidation" shipment. In the consolidation-deconsolidation case, marine containers containing goods destined to multiple RDCs are channeled through a common port and routed to a deconsolidation center (trans-load warehouse or cross-dock) located in the hinterland of the port of entry. The goods are unloaded from the marine containers, sorted, and re-loaded into fifty-three foot long domestic containers or trailers for final landside movement to the RDCs, possibly after some valued-added processing. Both direct and consolidation-deconsolidation shipments may use different landside transportation modes (channels) to RDCs; i.e., train, truck, and local drayage (dray).

Depending on the selected port of entry and the landside mode of transportation, the importer will face different transportation costs. Another source of cost is the opportunity cost of working capital tied up in the inventory throughout the supply chain. This cost is usually expressed as an interest rate times the amount of capital invested per unit of inventory times the average inventory level.

There are three types of inventories in the chain: cycle inventory, pipeline inventory, and safety stock. Cycle inventory is a function of the replenishment frequency (e.g., weekly) and is otherwise independent of the selection of the supply chain strategy and channel. Pipeline inventory is the amount of inventory in the pipeline between the origin and destination, and it is a function of the transportation time. Safety stock is the extra inventory kept by retailers to satisfy customer demands on time. Safety stock is maintained as a hedge against potential delays to shipments and potential errors in sales forecasts. It is a function of the customer service level,

the uncertainties in the shipment lead time, and the demand forecast error. Requiring a higher customer satisfaction level, or making use of supply channels that entail longer or more unreliable lead times, results in the need for larger safety stocks at RDCs.

The consolidation-deconsolidation strategy uses concepts of "postponement" and "risk pooling" to reduce the requirement for safety stocks at destination RDCs. By postponing the commitment to specific channels and RDCs, the importer can exploit an updated match-up of supply to demand to reduce safety stocks. The risky exposure to demand surges or supply shortages over the long lead times from Asian factories to the RDCs can be reduced to a relatively low-risk exposure over the short lead times from the trans-load warehouse to the RDCs. Furthermore, by pooling the forecast errors of demands at different RDCs together, served by a single port, importers face less uncertainty and can reduce the level of safety stocks. In typical practice, the contents of five forty foot marine containers fit into three or three and one-quarter fifty-three foot domestic containers or trailers that have much larger cubic capacities. The savings from fewer inland vehicle movements partially offsets the extra costs for the transportation infrastructure and for trans-load handling of goods associated with the consolidation-deconsolidation strategy.

Most importers make little or no investment in facilities upstream from the RDCs. They review their supply chain strategies annually. Their transportation, trans-loading, and import warehousing services are put out for bid, leading to annual contracts for such services provided by steamship lines, intermodal marketing companies, and third-party logistics providers. Thus, import supply chain strategies are static over a 12-month time frame but can be changed in minor ways or major ways from year to year in response to changing transportation or inventory economics.

Some retail importers are large enough such that they not only have the opportunity to employ trans-loading strategies, but are also able to employ multiple strategies for importing their portfolio of goods, possibly some via direct shipping and some via trans-loading. We will make some reasonable assumptions and show that their overall supply chain problem can be solved by running the single strategy optimization multiple times, and then utilizing a simple shortest path algorithm.

When the volume of any given shipment from the port to the RDC does not exactly match the size of a container (marine or domestic), importers will also have to handle less-than-container shipments. For a shipment that only takes up a fraction of the container's volume, the importer may be required to pay the full transportation costs, or a cost greater than that given fraction of the container's volume.

In this dissertation, we first examine a heuristic algorithm for the optimization of the annual supply chain strategy for a set of merchandise for importers of waterborne containerized goods from Asia to USA. This heuristic algorithm finds a near-optimal least-cost supply chain strategy for each set of goods for an importer, in terms of ports and landside transportation modes to be used. This algorithm allows the importer to select an efficient direct shipment or trans-loading strategy. The costs considered include costs for transportation and handling, pipeline inventory, and safety stock inventory held at RDCs. Here, we integrate a location-allocation problem with risk pooling, routing, and selection of transportation modes, while considering stochastic demand and random transportation time to achieve a desired customer satisfaction level. We discuss

shortcomings found in the original version of the heuristic, and specifically how these shortcomings were detected. We then suggest an improved heuristic that requires additional computational complexity but finds solutions guaranteed to be closer to optimal. Once the near-optimal strategy for each set of goods is determined, we propose a shortest path model to find the optimal set of strategies for the importer to ship all goods if a retailer has the capability to utilize multiple strategies for the importing of different goods within their product portfolio. We also discuss the impacts of shipments having less-than-container volume.

The performance of the proposed heuristic and network optimization is then compared with a baseline that is an approximation of the current set of strategies used by a case study large national importer. We then analyze the breakpoints between different strategies for retailers of different volumes and good valuations, as well as the volumes at which there is value in allowing a retailer to utilize multiple importing strategies. Finally, we examine the value of building redundancy into the importing supply chain to mitigate the cost of potential disruptions, based on including more ports in a trans-loading solution than would be found as optimal based on the proposed model.

The entirety of this model and analysis can be beneficial to many stakeholders of the supply chain, such as importers, public policy makers, port authorities, and landside transportation companies (trucks, railroad, drayage, etc.). These stakeholders need to consider the response of all importers to changes in import volume over time, services, rates, fees, or infrastructure, and so an algorithm that can rapidly calculate and tally supply chain channel volumes across all importers is of considerable interest. Throughout this dissertation, we assume there is enough capacity available in all ports and transportation channels, and therefore we do not consider capacity constraints.

The rest of the paper is organized as follows: in section two, we review literature applicable to import supply chain management and facility location. In section three, the data and the framework used by the model are introduced. In section four, our original and improved heuristics to find a single efficient strategy for a set of goods are discussed. In section five, we introduce a network optimization model to find the optimal set of strategies for a retailer, where each strategy is applied to a different segment of goods within the product portfolio. In section six, we discuss the case where a set of goods will cause less-than-container shipments, and how that impacts the results of the heuristic algorithm and the network optimization. In section seven, we examine the optimal single strategy for retailers of different importing volumes and declared good values, as well as analyzing the volumes at which it becomes worthwhile to utilize a multi-strategy solution. In section eight, we analyze the value of building redundancy into a retailer's supply chain based on potential supply chain disruptions. Finally, conclusions, recommendations, and directions for future research are presented in the last section.

2. Literature Review

As discussed in the introduction, the model developed in this dissertation can influence the practices of many stakeholders of the supply chain. In the domain of intermodal freight transport systems, Caris et al. (2008) provide an overview of the planning decisions and solution methods proposed in the scientific literature. The authors identify four types of decision-makers based on four main activities in intermodal freight transport: 1) drayage operators, who organize the

planning and scheduling of trucks between terminals and shippers and receivers; 2) terminal operators, who manage transshipment operations from road to rail or barge, or from rail to rail or barge to barge; 3) network operators, who are responsible for the infrastructure planning and organization of rail or barge transport; 4) intermodal operators, who are the users of the intermodal infrastructure and services and select the most appropriate route for shipments through the whole intermodal network. In each category decisions can be made at three levels: long-term strategic, medium-term tactical, and short-term operational. The authors find a lack of research on the strategic- and tactical-level issues of intermodal operators. All four types of decision-makers can benefit from our research. Intermodal decision-makers, in particular, can benefit from the proposed methodology in this dissertation to make better decisions at strategic and tactical levels.

The problem under study lies in the intersection of facility location and supply chain management (SCM) research areas. A general facility location problem considers a set of spatially distributed customers and a set of facilities to serve customer demands. Research in this domain addresses problems such as which facilities should be used (opened), and which customers should be assigned to which facility (or facilities) so as to minimize total costs (location-allocation problem). For recent reviews of facility location research we refer readers to ReVelle et al. (2008).

SCM deals with planning, implementing, and controlling the operations of the supply chain. SCM spans all movements and storage of raw materials, work-in-process inventory, and finished goods from the point-of-origin to the point-of-consumption. Historically, researchers have focused on elements of the chain rather than treating the supply chain as a whole. Here, we integrate the location-allocation problem with risk pooling, routing, and selection of transportation modes, while considering stochastic demand and random transportation time to achieve a desired customer satisfaction level.

Melo et al. (2009) provide a review of recent literature of facility location models in the context of supply chain management and report that the majority of the literature deals with deterministic environments, ignoring the uncertainties involved in location decisions. Their survey further shows that the facility location decision is frequently combined with inventory decisions. In contrast, routing and the choice of transportation modes (alone or integrated with other types of decisions) have not received much attention. Shen and Qi (2007), Ambrosino and Scutellà (2005), Ma and Davidrajuh (2005), Liu and Lin (2005), have considered routing decision-making simultaneous with inventory management. Wilhelm et al. (2005) have considered choice of transportation mode along with inventory management. Manzini and Bindi (2009) consider transportation mode selection along with routing and inventory management.

Managing inventory involves two key tasks: the first is to determine the number of stocking points; the second is to define the level of inventory to maintain at each of these points. Inventory control policies may be included in a facility location problem to recognize risk pooling benefits due to stochastic demands or randomness in supply. This combination of tactical and strategic decisions has been addressed by some authors - see Snyder et al. (2007), Shu et al. (2005), Miranda and Garrido (2004), Shen et al. (2003), Daskin et al. (2002), Erlebacher and Meller (2000). However, within the context of the location-allocation problem, there is a lack of publications which consider risk pooling simultaneously with choice of transportation mode and routing.

4

As discussed by Melo et al. (2009), the existing literature in location-allocation problem is still far from combining many aspects relevant to SCM. In fact, this integration leads to much more complex models due to the large size of the problems, in particular when tactical and operational decisions are integrated with strategic ones. The literature integrating uncertainty in SCM with location decisions is still scarce. Furthermore, many relevant tactical and operational decisions in SCM, as it is the case with routing and the choice of transportation modes, are far from being integrated with location decisions. In this dissertation, we target these gaps by addressing problems involving stochastic demand and random transportation time, while considering risk pooling, routing, and choice of transportation modes.

Chopra and Sodhi (2004) discuss the causes and potential methods to manage supply chain breakdowns. In the section on redundancy, we will focus mostly on what they term as "disruptions" and "delays". Examples of these would be natural disasters, labor disputes, and excessive handling at border crossings or as transportation modes change. Snyder and Daskin (2005) describe a facility location problem with expected failure cost, specifically focusing on the idea of "backup" assignments, representing the facilities to which customers are assigned when lower cost facilities fail. Cui et al. (2010) extend this problem and solve through two methods: a mixed integer program and a continuum approximation methodology. Snyder et al. (2006) discuss how to design a supply chain that is resilient to disruption, introducing a worst case cost model. Lim et al. (2010) examine this problem when a facility can be made resistant to disruptions by paying an additional cost. Snyder (2006) provides a review of many of these problems. However, all of these models focus on the transportation costs incurred in a facility location model. They do not take into account inventory costs. A more qualitative understanding of how to build a resilient supply chain can be found in Christopher and Peck (2004).

Except for Leachman (2008) and Jula and Leachman (2011), the problem as outlined in previous section of this dissertation has not been addressed by researchers. In particular, note that most research has dealt with the challenges posed by potential investments in intermediate warehouses in the supply chain, which, because of the outsourcing in annual service contracts, is not a concern here. Leachman (2008) assumes a single homogenous supply chain strategy for each importer. Using the results of a heuristic, the author investigates the effect of increasing container fees at a San Pedro Bay port in terms of diversion of cargoes to other ports.

In this dissertation, we adopt the framework of the data and the structure of the supply chain suggested by Leachman (2008), and subsequently by Jula and Leachman (2011). In addition, here we introduce a network optimization methodology for the problem when an importer is allowed to employ multiple supply chain strategies, each for a different subset of its overall portfolio of imported goods. Using our heuristic, we provide general recommendations for importers to choose supply chain strategies most suitable for their businesses.

3. Data Sources

For this research, we procured data from a large big-box national retail chain, on their transportation and handling costs via all channels and strategies, landside and across-the-water transit times, and import volumes during different times of the year.

We secured US customs data for year 2006 as summarized in the PIERS (http://www.piers.com/) commercial data subscription. These data specify the total volumes of imports from Asian origins (measured in twenty-foot equivalent units, or TEUs) for each US port, each importer, and each of 99 commodity codes. We also secured the customs data for year 2006 as summarized in the World Trade Atlas commercial data subscription, which summarizes total volumes of imports to the Continental USA from Asian origins by total declared value for each of the 99 commodity codes. Given these data, we were then able to make estimates for volumes and declared values per cubic foot by commodity type for general retailers. We then assumed a comparable value distribution for the big-box retailer, as this particular chain sells goods encompassing the entire value spectrum.

The major North American ports of entry are as follows:

1) Vancouver, BC (VAN); assumed no trans-loading through this port, only direct shipment of marine containers (to USA destinations).

2) Seattle – Tacoma, WA (SEA); assumed trans-loading is allowed.

3) Oakland, CA (OAK); assumed trans-loading is allowed.

4) Los Angeles – Long Beach, CA (LA-LB); assumed trans-loading is allowed.

5) Lazaro Cardenas, Mexico (LAZ); assumed no trans-loading.

6) Houston, TX (HOU); assumed trans-loading is allowed.

7) Savannah, GA (SAV); assumed trans-loading is allowed.

8) Charleston, SC (CHA); assumed no trans-loading.

9) Norfolk, VA (NOR); assumed trans-loading is allowed.

10) New York – New Jersey (NY-NJ); assumed trans-loading is allowed.

11) Prince Rupert, BC (PRU); assumed no trans-loading.

There are other ports handling Asian imports to USA, but in much smaller volumes than handled by the above ports. Other important data concern mean and standard deviation statistics on container dwell times in port terminals, and on container flow times in landside channels, as reported in private communications from major importers, terminal operators, and railroads.

In our study, the continental United States is divided into 24 regions corresponding to the RDCs employed by the case study retailer, with the entire import demand for each region concentrated at a single location. In actuality, the retailer employs 26 RDCs in the continental United States. However, two pairs of these RDCs are in such close proximity to each other geographically that we chose to combine them (Fontana, CA & Rialto, CA, and Wilton, NY & Amsterdam, NY). We believe these pairs of facilities simply handle distribution of different portions of the product portfolio within the same regions.

Costs to ship imports from the ports of Qingdao, Shanghai, Ningbo, Xiamen, and Yantian in mainland China to the ports of entry in the United States were provided by the retailer as of

2010. For each port of entry and each destination, 2010 rates were provided for two alternative supply chain channels: (1) shipping marine containers direct from Asia to RDC destinations; and (2) shipping marine containers to trans-loading warehouses in the hinterlands of the ports of entry, thence re-loading the imports in domestic rail containers or truck trailers for re-shipping from trans-loading warehouses to regional destinations.

In many cases, the retailer did not provide transportation rates for certain channels, as they are not currently in use. For these channels, costs to importers for routing imports were developed. Year 2007 rate quotations to various importers from steamship lines, non-vessel-operating common carriers, intermodal marketing companies, trans-loading warehouse operators, railroad carriers, and trucking companies were obtained. Considerable variation in rates from carrier to carrier and customer to customer was encountered. Average rates were developed from a basket of rates for each channel. Year 2010 fuel recovery surcharges were applied.

We have observed in practice that typically each RDC is supplied using only one channel. Volume is concentrated on a channel in order to negotiate a favorable rate as well as to simplify information management. We have therefore assumed in the model below that for a particular set of goods each RDC must be replenished using a single port and a single landside channel. We assume independent and identically distributed normal random variables for both demands and lead times, with no correlation among these variables.

4. Heuristic Algorithm for Solving the Single Strategy Model

Here we examine a heuristic algorithm to find the single strategy which optimizes the distribution of import volumes by port and landside channel for a given port and transportation infrastructure network. This algorithm helps the importers to select ports of entry and landside channels so as to minimize their total cost of transportation and handling, pipeline inventory, and safety stock inventory at RDCs. This algorithm selects either a direct shipment or trans-loading strategy for a set of goods. Here we assume each RDC is served only by one port using one mode of transportation. We do not consider capacity constraints or minimum contracted volumes. While there are certainly capacity limitations on ports, terminals, and rail lines, no single importer imports enough volume to cause such limits to be reached. (The largest importer of Asian goods to the USA, Walmart, accounts for only about 10% of such imports.) Contracts negotiated with transportation carriers may require certain minimum volumes, but we assume here that our model is to be applied at the pre-negotiation stage to identify the best supply chain strategy to be pursued by the importer in negotiations with carriers. Figure 4-1 displays a schematic of the optimization model and the required inputs and generated outputs.
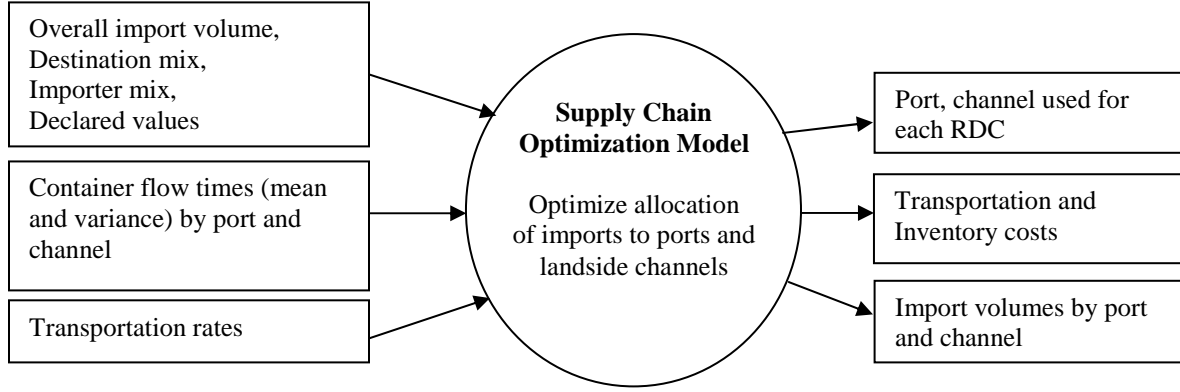
Figure 4-1. Inputs & outputs of the supply chain model

4.1. Notation for Parameters

We follow the notation and basic model as set out in Jula and Leachman (2011) and adapt it for our purposes.

n – index of set of RDCs;

m – index of set of ports of entry (POEs);

i – index of set of land transportation modes (channels). We will let $i \in DIR$ if it utilizes a direct shipping methodology and $i \in TL$ if it utilizes trans-loading;

D – nationwide average sales volume for the importer per week (expressed in TEUs);

E – MAPE – mean absolute percentage error (expressed as a fraction of one) in one-week-ahead forecasts of nationwide sales for the importer;

σ^D – standard deviation of errors in one-week-ahead forecasts of nationwide sales. A standard assumption is $\sigma^D = 1.25 E \cdot D$ (see, e.g., Silver and Peterson, 1985, based on D being a normal random variable);

D_n, σ_n – mean (D) and standard deviation (σ) of sales distributed from RDC n. It is assumed that $\sum_n D_n = D$ and the proportion of nationwide sales handled by each RDC is fixed;

R – time between replenishment orders (from Asian suppliers). In this dissertation, R is always assumed to be 1 week;

L^A – mean value of the lead time (expressed in weeks) from when a nationwide replenishment order is placed until an allocation of the order among USA ports of entry is fixed and vessel passages are booked;

L_m^M, σ_m^M – mean (L) and standard deviation (σ) of the lead time (expressed in weeks) for shipments from point of origin to port of entry POE m, measured from when vessel passage is booked until land transport to RDC from POE m begins (direct shipping case), or until land

8

transportation to destination RDC from POE m is booked (consolidation-deconsolidation case);

L_m^S, C_m^S – mean value (L) of the lead time (expressed in weeks), and transportation cost (C) per unit of load, from departure from point of origin until land transport from POE m to RDC begins (direct shipping), or until land transport from POE m to destination RDC is booked (consolidation-deconsolidation);

$L_{m,n,i}^N$, $\sigma_{m,n,i}^N$, $C_{m,n,i}^N$ – mean value (L) and standard deviation (σ) of transportation lead times (expressed in weeks), and transportation cost (C) per unit of load, shipped using land transportation mode i, from departure from POE m until processed through RDC n (direct shipping); or from when land transport from POE m to RDC n is booked until processed through the RDC n (consolidation-deconsolidation);

z – safety factor determining the level of safety stocks at RDCs. (Choosing $z = 2.05$ implies approximately a 98% probability of no stock-out.) In this dissertation, it is assumed that all RDCs have the same customer satisfaction level of $z = 2$;

V^S – the amount of capital tied up in a unit of pipeline stock from origin to POE;

V^N – the amount of capital tied up in a unit of pipeline stock from POE to RDC;

V^R – the amount of capital tied up in a unit of RDC safety stock (assumed to be the same for all RDCs in this dissertation);

r – inventory carrying rate (inventory holding cost rate).

4.2. Variables

$\delta_{m,n,i}$ – binary variable (0 or 1) indicating if land transportation mode i is used for transportation from departure from POE m to RDC n. This variable is set to zero if land transportation mode i cannot be used for transportation from m to n;

Ω_m – set of RDCs served using port m using a trans-loading transportation mode;

ss – positive continuous variable showing the total safety stock in the chain.

4.3. Constraints

$$\sum_m \sum_i \delta_{m,n,i} = 1 \qquad \forall n \tag{1}$$

Constraint (1) guarantees that each RDC is served; and it is served only by one port and one mode of transportation.

$$\Omega_m = \{n \mid \delta_{m,n,i} > 0, i \in TL\} \quad \forall m \tag{2}$$

9

Constraint (2) defines the set of RDCs that are served by port *m* using a trans-loading transportation mode.

4.4. Objective Function

Our objective is to minimize the total cost (total cost = transportation cost + inventory holding cost). The cost of the cycle stock has been omitted because that cost is independent of the supply chain channel alternative. Formula (3) shows the total transportation cost.

$$\sum_m \sum_n \sum_i ((C_m^S + C_{m,n,i}^N)\delta_{m,n,i}D_n) \tag{3}$$

The inventory holding cost is due to the pipeline inventory cost and the required safety stocks. The terms of formula (4) show the pipeline inventory cost from Asia to POEs and the pipeline inventory cost from POEs to RDCs respectively.

$$(r)\sum_m \sum_n \sum_i (V^S L_m^S \delta_{m,n,i} D_n) + (r)\sum_m \sum_n \sum_i (V^N L_{m,n,i}^N \delta_{m,n,i} D_n) \tag{4}$$

Formula (5) shows the inventory holding cost due to the safety stock, which we expand in the following section.

$$(r)(V^R)(ss) \tag{5}$$

4.4.1. Calculating the Safety Stocks

Eppen (1979) showed that significant inventory cost savings can be achieved by grouping demands of customers together, and thus capitalizing on "risk pooling effects". Using Eppen's risk pooling result, the amount of safety stock required to ensure that stock-outs occur with a probability of α or less is $z_\alpha\sqrt{N\sum\sigma_n^2}$, where *N* is the number of demand locations (nodes) pooled together and σ_n is the standard deviation of the demand at node *n*. The safety stock is proportional to the square-root of the number of pooled demands ($\sqrt{N}$) in the consolidation case, while the safety stock required for separate inventories in the direct shipment case is proportional to the number of demand nodes (*N*).

Eppen and Schrage (1981) consider a depot-warehouse echelon system, where the depot serves several warehouses and does not hold any inventory itself. The authors derive a closed form expression for the order-up-to level assuming an equal fractile allocation for identical warehouses with constant (zero variance) shipment lead times. Equal fractile is a form of fair-share policy which is the optimal rationing policy for base stock control under the cost structure presented. Such a system takes advantage of reduced inventory because of a portfolio effect over the lead time from the supplier (joint ordering effect). The port-RDC structure in our study has similar characteristics: ports do not hold inventories, and all inventories are held at RDCs. Using Eppen and Schrage (1981) results, and in the simple case in which all RDCs are replenished by

trans-loading through one port with common lead times, (i.e., $L_m^M = L_0^M$, $L_{m,n,i}^N = L_0^N$, $\forall\, m,n,i$), the total safety stock can be calculated as:

$$(z)\sqrt{(L^A + L_0^M)(\sigma^D)^2 + (N)^2(L_0^N + R)\left(\frac{(\sigma^D)^2}{N}\right)},$$ (6)

which shows the square-root effect on the pooled demand over the supply chain route from the supplier to the port.

Considering variability in the lead time significantly increases the required safety stock. In the simplest form of one supply node and one demand node considering lead time (with mean L, and standard deviation of σ^L) and no risk pooling, safety stock can be expressed as (Silver and Peterson, 1985):

$$(z)\sqrt{(L + R)(\sigma^D)^2 + D^2(\sigma^L)^2}$$ (7)

In the case of N identical RDCs with common mean and variance for lead times ($\sigma_m^M = \sigma_0^M$, $\sigma_{m,n}^N = \sigma_0^N$, $\forall\, m,n$), using equations (6) and (7), Leachman (2008) derives the total safety stock for direct shipment and trans-loading as formulas (8) and (9), respectively.

$$(z)\sqrt{(L^A)(\sigma^D)^2 + N^2(L_0^M + L_0^N + R)\left(\frac{(\sigma^D)^2}{N}\right) + D^2\left((\sigma_0^M)^2 + (\sigma_0^N)^2\right)}$$ (8)

$$(z)\sqrt{(L^A + L_0^M)(\sigma^D)^2 + N^2(L_0^N + R)\left(\frac{(\sigma^D)^2}{N}\right) + D^2\left(\frac{(\sigma_0^M)^2}{N} + (\sigma_0^N)^2\right)}$$ (9)

Formula (9) is meaningful for the case where multiple containers are shipped in each review interval to the trans-loading center and lead time uncertainties across the individual container shipments are independent. Like Eppen and Schrage, Leachman assumes the equal fractile allocation policy which aims to equalize the stock-out probabilities at the end stock points (i.e., the RDCs).

Bollapragada et al. (1999) showed that the results of Eppen and Schrage (1981) still apply even in situations where there are non-identical warehouses. The authors show the fair share for node n, out of the required safety stock for the pooled nodes set of J, will be proportional to the ratio of $\dfrac{\sigma_n}{\sum_{v \in J} \sigma_v}$, assuming the same customer satisfaction level is to be maintained at all nodes.

Using this result, Jula and Leachman (2011) further derived total safety stock for direct shipping and trans-loading for RDCs that do not have identical mean and variation in demand. They assumed that the nationwide normal demand is a linear combination of normal random demands at each of the RDCs. Under common lead times, the total safety stock for direct shipment and trans-loading are given by equations (10) and (11) respectively.

11

$$ss = z \sum_m \sum_n \sum_{i \in DIR} \delta_{m,n,i} \left[L^A \sigma_n^2 \frac{\sum_v \sigma_v^2}{(\sum_v \sigma_v)^2} + \sigma_n^2 \left(L_m^M + L_{m,n,i}^N + R \right) + D_n^2 \left((\sigma_m^M)^2 + (\sigma_{m,n,i}^N)^2 \right) \right]^{1/2} \quad (10)$$

$$ss = z \sum_m \sum_n \sum_{i \in TL} \delta_{m,n,i} \left[\begin{array}{l} L^A \sigma_n^2 \dfrac{\sum_v \sigma_v^2}{(\sum_v \sigma_v)^2} + \sigma_n^2 L_m^M \dfrac{\sum_{v \in \Omega_m} \sigma_v^2}{(\sum_{v \in \Omega_m} \sigma_v)^2} + \sigma_n^2 \left(L_{m,n,i}^N + R \right) \\[2em] + D_n^2 \left(\dfrac{\sum_{v \in \Omega_m} D_v^2}{(\sum_{v \in \Omega_m} D_v)^2} (\sigma_m^M)^2 + (\sigma_{m,n,i}^N)^2 \right) \end{array} \right]^{1/2} \quad (11)$$

4.5. Heuristic Algorithm

The simplest setting of the problem under study can be translated to a *p*-median problem, in which *p* facilities are to be selected to minimize the total (weighted) distances or costs for supplying customer demands. In addition, we consider more complexities such as the inventory costs, which are nonlinear in the assignment variables, and the selection of transportation modes in a multi-echelon setting. Thus, the problem we are studying is more difficult than the standard *p*-median problem, which is already a well known NP-hard problem (see ReVelle et al., 2008).

A Mixed Integer Non-Linear Programming (MINLP) approach is discussed in Jula and Leachman (2011), which allows for mixed strategies of trans-loading and direct shipments for the same set of goods. That is, there are valid solutions such that some port-RDC combinations are serviced by direct shipping, while others employ trans-loading. But in the heuristic, for a set of goods we only allow one homogeneous strategy selected from among a set of fixed strategies. This more accurately describes the types of strategies that most retailers will be willing to analyze and utilize in their supply chains. For the case study retailer, we generated 15 potential strategies, some actually practiced by the retailer as well as others that they could conceivably explore given their current infrastructure. A sample of the potential strategies include:

1) TL-LA: Consolidate-deconsolidate and trans-load using a warehouse in the hinterland of the Ports of Los Angeles and Long Beach (LA-LB) only. Importers of expensive goods, difficult-to-forecast goods and goods experiencing rapid obsolescence have been observed to practice TL-LA supply chains. Such supply chains permit inventory to be managed as tightly as possible, albeit with transportation costs higher than for other alternatives. LA-LB is chosen as the single port of entry because Southern California is the largest local market, and so transportation costs are minimized compared to using a different single port of entry.

2) TL-2-Sav: Consolidate-deconsolidate and trans-load using warehouses at both LA-LB and Savannah. Compared to TL-LA, this strategy can reduce transportation costs by making use of all-water transit to a deconsolidation center located on the East Coast. However, safety stocks and pipeline inventories are increased.

3) TL-2-WC: Consolidate-deconsolidate and trans-load using warehouses at both LA-LB and Seattle (WC short for West Coast). As in TL-2-Sav, safety stocks and pipeline inventories are increased. There may additionally be favorable rates through Seattle that would make up for the increased distance from East Coast RDCs.

4) TL-3-Sav: Consolidate-deconsolidate and trans-load using warehouses at LA-LB, Seattle, and Savannah. Compared to TL-2-Sav or TL-2-WC, transportation costs are reduced further, but safety stock requirements are increased. This or a similar strategy is employed by the case study retailer for much of its import portfolio.

5) Direct-WC: Direct-ship marine containers to RDCs considering use of only West Coast ports. Small and regional importers of relatively expensive goods have been observed to practice such an import supply chain strategy.

6) Direct-All: Direct-ship marine containers to RDCs considering use of all ports. This strategy is commonly adopted by importers of low-value goods and by small importers with insufficient volume to effectively practice consolidation-deconsolidation. It offers the potential for lowest transportation and handling costs, in exchange for inventory requirements greater than that of the alternatives.

The other nine strategies included for the heuristic utilize trans-loading in various combinations of ports.

The original heuristic presented in Jula and Leachman (2011) is as follows.

Step 1.	**for** every strategy s selected from the set of strategies S, **do**
Step 2.	**for** every n in the set of RDCs, **do**
Step 3.	**for** every port m in M_s (set of ports available in strategy s), **do**
Step 4.	**for** every land transportation mode i used in strategy s, **do**
Step 5.	Calculate transportation cost using formula (3)
Step 6.	Calculate pipeline inventory cost using formula (4)
Step 7.	**end for**
Step 8.	**end for**
Step 9.	Select port $\bar{m}$ and land transport mode $\bar{i}$ such that the transportation cost + pipeline inventory cost is minimized for selected n
Step 10.	Set $\delta_{m,n,i} = 1$ for $m = \bar{m}$, $i = \bar{i}$, and set $\delta_{m,n,i} = 0$ for all other m and i
Step 11.	**end for**
Step 12.	For trans-loading strategies, generate the set Ω_m for all m using constraint (2)
Step 13.	Calculate the total safety stock ss using equation (10) for direct shipping strategies or equation (11) for trans-loading strategies
Step 14.	Calculate the total cost = total transportation cost + pipeline inventory cost + safety stock cost using formulas (3), (4), and (5)
Step 15.	**end for**
Step 16.	Select the best strategy s^* which minimizes the total cost
Step 17.	For s^*, report the total cost, and the ports and channels used for each RDC

4.6. Anomaly and Shortcomings of the Original Heuristic

In the course of simulation experiments on this heuristic model using a set of importers designed to model the entire US importing supply chain, an interesting anomaly was discovered. As described in the details of the heuristic, the total cost for each importer is not solved optimally. For given supply chain structural alternatives (Direct Shipping, TL-3-Sav, TL-2-WC, TL-LA, etc.), the heuristic finds the port and landside channel routings offering least total transportation plus pipeline inventory costs to serve each RDC, computes the safety stock required for that routing strategy, and then compares total costs for each structural alternative.

In some scenarios we simulated, for many importers there are alternative supply chains utilizing different land transport channels that have total costs that are very similar (less than 0.2% difference), yet total volume allocations by port and by landside channel that are very different. While the heuristic consistently provides near-optimal solutions in terms of total supply chains costs, it is difficult for the heuristic to determine optimal volumes by ports and landside channels when there are very disparate solutions whose costs are very similar.

In two of our tests on a particular parameter set of transportation rates and set of importers, we imposed hypothetical port wharfage fees at the LA-LB ports of $150 and $200 respectively. There were many importers that showed the following pattern: In the $150 fee scenario, the heuristic selected the "TL-4" strategy, using four ports across the US for trans-loading; in the $200 fee simulation, the heuristic selected the "TL-LA" strategy. For these importers, increasing the fees at LA-LB actually caused more goods to be shipped in through that port. This is clearly not the behavior one expects.
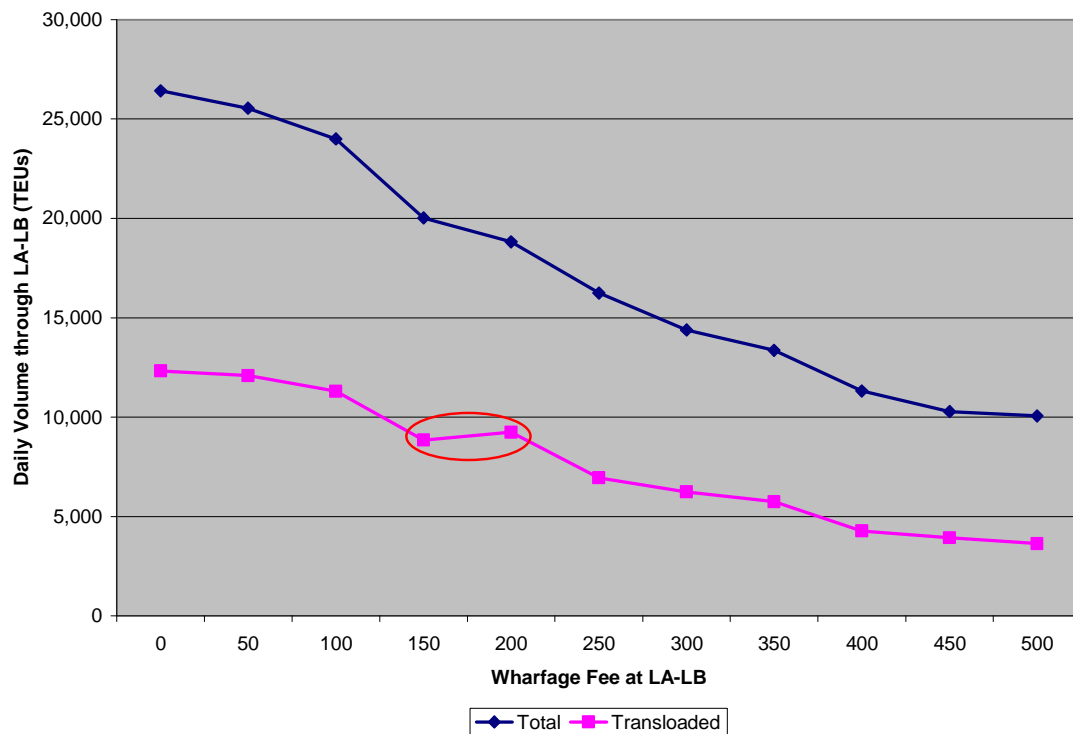

Figure 4-2. Total and Trans-loaded Volume through LA-LB at Different Wharfage Fees for this Particular Parameter Set under the Original Heuristic

14

After some investigation, we discovered the cause of this anomaly. For some specific importers, we found the following pattern: For a LA-LB wharfage fee of $150 under the TL-4 strategy, imports destined to most RDCs would have the lowest transportation cost via the port of LA-LB. Thus, there would not be a substantial difference in the safety stock costs between the TL-4 and TL-LA strategies, as most of the stock would remain pooled at LA-LB. That is, the particular nature of the TL-4 strategy selected involved very heavy use of LA-LB. (See Appendix A, Table A-1.) The savings in transportation cost under TL-4 would outweigh the minor increased cost from splitting safety stock between the 4 ports (because most of the volume remained pooled via LA-LB anyway). Thus, the heuristic found the TL-4 strategy to be optimal.

However, at a wharfage fee of $200, only about half of the RDCs would have lowest transportation cost via LA-LB, while the rest would now have lowest cost via Seattle. In this scenario, the safety stock would be more evenly split, and due to the square-root nature of reductions from pooling, the retailer would need to hold more total safety stock. Now, even though transportation cost shows increased savings when using non-LA-LB ports, it is outweighed by the increase in safety stock required by splitting the shipments. Therefore, the heuristic would choose to keep the safety stock pooling benefit and would use the TL-LA strategy. (See Appendix A, Table A-2.) Thus, we saw the counter-intuitive result of increased wharfage fees leading to more retailers selecting the TL-LA strategy, which causes increased shipment through LA-LB.

4.7. Improved Heuristic

The investigation of this anomaly then suggested an improvement to the heuristic as follows: For each trans-loading strategy, we identify a "first pass" port. We will begin testing a strategy with all RDCs having their goods shipped and trans-loaded through that "first pass" port. (Note that for our test cases, LA-LB was always designated as the "first pass" port for any strategies that included multiple ports of entry.) Next, we consider expanding that strategy by utilizing the other ports of entry available in that strategy. Consider shifting each RDC to its cheapest eligible port of entry in terms of transportation plus pipeline inventory costs, as in the original heuristic. We rank the RDCs by potential transportation plus pipeline inventory cost savings from shifting the RDC from the "first pass" port to its cheapest port of entry.

Now, instead of forcing the shipment to be split solely by which port offers the lowest transportation plus pipeline inventory cost to each RDC, we step through the RDCs one at a time in order of transportation plus pipeline inventory cost savings, and then calculate the total cost (transportation + pipeline inventory + safety stock). That is, we first consider shifting just the highest-ranked RDC, and see if the total costs are reduced from the case of shipping all volume through the "first pass" port. Then we consider shifting the two highest-ranked RDCs and see if the total costs are reduced. Then we consider shifting the three highest-ranked RDCs, and so on. Note that we will never shift those RDCs whose cheapest port of entry is already the "first pass" port. We will then take the RDC-to-port assignment within that strategy that has the minimum total cost. By adding this additional step to the algorithm, we will never be required to split the shipment if there exists an assignment where the loss of safety stock pooling benefits would be greater than the additional cost of transportation.

The procedure of the updated heuristic is as follows.

Step 1.	**for** each strategy s selected from the set of strategies S, **do**
Step 2.	Identify "first pass" port $m_{s,0}$
Step 3.	**for** each n in the set of RDCs, **do**
Step 4.	**for** each port m in M_s (set of ports available in strategy s), **do**
Step 5.	**for** each land transportation mode i used in strategy s, **do**
Step 6.	Calculate transportation cost using formula (3)
Step 7.	Calculate pipeline inventory cost using formula (4)
Step 8.	**end for**
Step 9.	**end for**
Step 10.	Select port $\overline{m}$ and land transport mode $\overline{i}$ such that the transportation cost + pipeline inventory cost $= \lambda_n$ is minimized for selected n
Step 11.	Select land transport mode $i_{n,0}$ such that the transportation cost + pipeline inventory cost $= \mu_n$ is minimized for selected n and $m = m_{s,0}$ "first pass" port
Step 12.	**end for**
Step 13.	Order RDCs as $\{[1], [2], …, [N]\}$ as decreasing in $\mu_n - \lambda_n$, where $N = |\text{RDCs}|$
Step 14.	**for** $k = 0$ to N
Step 15.	Set $\delta_{m,[n],i} = \begin{cases} 1, & [n] > k, m = m_{s,0}, i = i_{[n],0} \\ 1, & [n] \le k, m = \overline{m}, i = \overline{i} \\ 0, & otherwise \end{cases}$
Step 16.	For trans-loading strategies, generate the set Ω_m for all m using constraint (2)
Step 17.	Calculate the total safety stock ss using equation (10) for direct shipping strategies or equation (11) for trans-loading strategies
Step 18.	Calculate the total cost = total transportation cost + pipeline inventory cost + safety stock cost using formulas (3), (4), and (5)
Step 19.	**end for**
Step 20.	Select the best k^* that minimizes the cost for strategy s
Step 21.	For k^*, report the total cost, and the ports and channels used for each RDC for strategy s
Step 22.	**end for**
Step 23.	Select the best strategy s^* which minimizes the total cost
Step 24.	For s^*, report the total cost, and the ports and channels used for each RDC

As previously mentioned, in all cases where a strategy included multiple ports, our choice of "first pass" port was LA-LB. Note that when $\overline{m} = m_{s,0}$, $\mu_n - \lambda_n = 0$ and the "first pass" port is optimal.

The foregoing heuristic is designed such that all the constraints of the MINLP problem are satisfied. The solution is generated very efficiently in terms of speed, and is feasible for the MINLP problem. However, there is no guarantee of optimality of the solution. In simulations, the optimality gap of the simplified heuristic was found to be generally less than 1%, and often less than 0.5%. In Jula and Leachman (2011), the MINLP was solved to optimality based on a genetic algorithm/hybrid method solver.

The total cost found by the original heuristic will be an upper bound to the cost found by the updated heuristic. This will be because for each strategy, the last iteration in the updated

heuristic will generate the same port-RDC allocations and costs as the single iteration for that strategy in the original heuristic, assigning every RDC to its respective cheapest port in terms of transportation cost + pipeline inventory cost. Therefore, the best cost for each strategy and thus for each importer in the updated heuristic must be less than or equal to the best cost in the original.

Using the updated heuristic will tend to allocate more volume to the "first pass" port, as there will be more opportunities to keep volume in that port. Let us examine the difference between the two heuristics for one example: $150 LA-LB wharfage fee. Using the updated heuristic, we see that, including all importers, over 1,500 TEUs per day are shifted from Seattle to LA-LB, with another 600 from NY-NJ and 150 from Savannah. This is a total increase of over 10% to imports through LA-LB. However, the cost benefit is negligible: including all importers, a savings of $160,000 per day as compared to a total cost of over $141 million, or just over 0.1%.
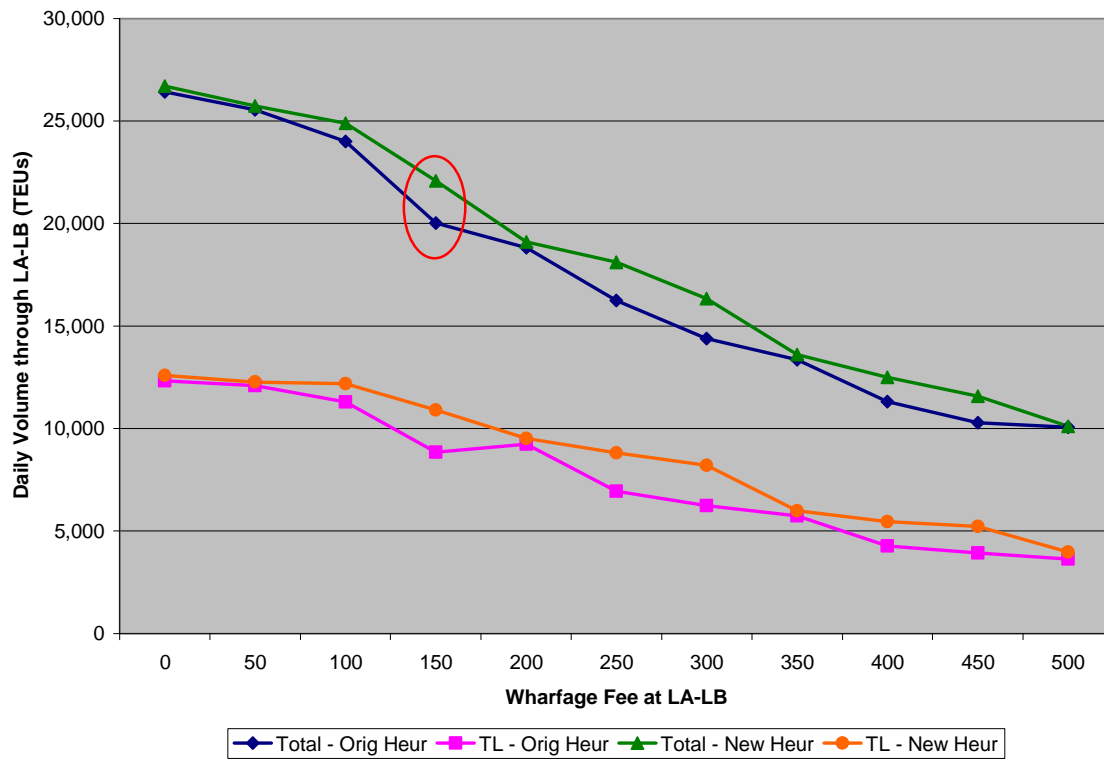

Figure 4-3. Total and Trans-loaded Volume through LA-LB at Different Wharfage Fees for this Particular Parameter Set Heuristic Comparison

The updated heuristic requires more run time, as we need to increase the number of total cost checks, an increase that is linear in the number of RDCs. In our test cases, we found that it would increase the run time by a factor of between 1.5 and 4, depending on the various cost parameters. For those cases where the "first pass" port offers higher transportation + pipeline inventory costs, the heuristic will take longer. This is due to the fact that more RDCs will need to switch from the "first pass" port to their cheapest ports.

This additional step does not guarantee that no other anomalies similar to the one noted above will occur. The choice of strategies and "first pass" port will have a great effect on

whether or not such an anomaly may occur. However, the original anomaly example above was fixed using the updated heuristic with LA-LB as the "first pass" port in all multiple port trans-load strategies, and we no longer saw cases where increased wharfage fees at LA-LB led to increased volume there. (See Appendix A, Table A-3.)

While this updated heuristic is guaranteed to have a lower cost than the original, it is still not guaranteed to find an optimal solution. For example, let us define a toy problem with 4 RDCs: LA-LB, Seattle, NY-NJ, and Minneapolis; and 3 possible ports: LA-LB, Seattle, and NY-NJ. We will define LA-LB as the "first pass" port. In order of transportation + pipeline inventory cost savings over the LA-LB port, we will describe the following:

RDC	Cheapest Port of Entry	Transportation + Pipeline Inventory Cost Savings over LA-LB
Seattle	Seattle	30
NY-NJ	NY-NJ	20
Minneapolis	Seattle	10
LA-LB	LA-LB	0

In this small example, the updated heuristic will only test the following assignments:

RDC	Assignment 1	Assignment 2	Assignment 3	Assignment 4
Seattle	LA-LB	Seattle	Seattle	Seattle
NY-NJ	LA-LB	LA-LB	NY-NJ	NY-NJ
Minneapolis	LA-LB	LA-LB	LA-LB	Seattle
LA-LB	LA-LB	LA-LB	LA-LB	LA-LB

There are three other assignment possibilities that could potentially show a lower cost that this heuristic will not check:

RDC	Unchecked Assignment 1	Unchecked Assignment 2	Unchecked Assignment 3
Seattle	Seattle	Seattle	LA-LB
NY-NJ	LA-LB	Seattle	NY-NJ
Minneapolis	Seattle	Seattle	LA-LB
LA-LB	LA-LB	LA-LB	LA-LB

As shown by Unchecked Assignments 1 and 3, it will never skip over a "shift" if it finds the total costs to be too high. As shown by Unchecked Assignment 2, it will only ever assign an RDC to either the "first pass" port or its port of cheapest transportation + pipeline inventory cost.

As such, there is another potential improvement to be made to the heuristic. Instead of choosing a single "first pass" port for each strategy, all of the ports in a given strategy could be considered "ordered". Ports would then be made "available" for use in this order. This would add additional cost calculations in step 10, as well as add another **for** loop between steps 12 and 13 in the updated heuristic as we step through each port as it is made "available". In this manner, we could consider checking some, but not all, of the above Unchecked Assignments. For example, if the ports in a strategy are ordered as {LA-LB, Seattle, NY-NJ}, the port of NY-NJ would not be made available for use until stepping through the RDCs using LA-LB and

Seattle only. In this further updated heuristic, one of Unchecked Assignments 1 and 2 would be tested. If the transportation + pipeline inventory cost to NY-NJ is cheaper through LA-LB, then Unchecked Assignment 1 would be tested; if the costs to NY-NJ is cheaper through Seattle, then Unchecked Assignment 2 would be tested. If the ports are ordered as {LA-LB, NY-NJ, Seattle}, then Unchecked Assignment 3 would be tested. As we are only adding more assignments to be checked and not removing any, this "ordered ports" version of the heuristic would produce results that are guaranteed to generate an equal or lower cost than the "first pass" version of the heuristic.

Based on tests with our current set of data, there is limited marginal improvement in using this further updated heuristic. The additional complexity in this "ordered ports" heuristic does not seem to be worthwhile, especially given the prominence and importance of risk pooling and trans-loading through LA-LB in the United States. However, given a more generic problem, this further improved heuristic may indeed end up being beneficial, even with the added complexity.

5. Network Optimization for Multiple Strategies

For a retailer, we will assume that instead of a homogeneous importing volume, a single average declared value, and average holding rate, we now have a discrete distribution of imported goods. That is, each retail importer will have a set of importing volumes, each volume having its own average declared value and average holding rate. We would expect that the weighted average (weighted by volume) of declared values would be equivalent to the overall average declared value, and the weighted average of holding rates would be equivalent to the overall average holding rate. Therefore, the problem becomes selecting which optimal strategy each value bin should employ, and which bins can be combined under the same optimal strategy.

5.1. Shortest Path Model

As the inventory holding cost increases, the cost of safety stock will grow, eventually growing large enough to dominate the costs of transportation. As shown in Jula and Leachman (2011), direct shipping is likely to be the optimal strategy for cheaper goods, a multiple port trans-loading strategy is likely to be optimal for goods with medium value, and a single port trans-loading strategy is likely to be optimal for the most expensive goods. As goods with similar valuations will use similar strategies, we can assume that we will only ever combine value bins with consecutive inventory holding rate values under the same optimal strategy. It will not make sense for two non-consecutive bins to share the same optimal strategy, while a bin with an inventory holding rate between those two employs a different optimal strategy.

We can then examine each set of combined bins as if it were a separate retailer. We will only need to examine sets of combined bins that are combinations of consecutive bins; thus instead of having an exponential number of sub-problems, we will only have $\left(B+1\right)B\big/2$ sub-problems, where B is the number of value bins. For example, if we have 4 value bins, we will examine the sub-problems for the following sets, where the set (a, b) includes all bins between the a-th and b-th inclusive: {(1,1), (1,2), (1,3), (1,4), (2,2), (2,3), (2,4), (3,3), (3,4), (4,4)}. We will take the declared value inventory holding rate of the set as the weighted average (weighted by volume) of the declared value inventory holding rates for the included bins. That is, given bin inventory

holding rate values $\rho_j = V_j r_j$, and bin demands D_j for $j = (1,\ldots,B)$, for set (a, b) we will let

$$\rho_{ab} = \frac{\sum\limits_{j=a}^{b} \rho_j D_j}{\sum\limits_{j=a}^{b} D_j}.$$ The total demand for set (a, b) would simply be $D_{ab} = \sum\limits_{j=a}^{b} D_j$.

We can then use the heuristic algorithm to determine the optimal strategy and minimum cost for each set of combined bins. Each of these sets of combined bins will now have a single optimal strategy and optimal cost. To get the total optimal cost for the retailer and the set of optimal strategies, we will need to select a set of the combined bin sets as defined above such that all value bins are covered. For example, a valid solution would be the sets {(1,1), (2,3), (4,4)}, which does include all bins 1-4. Other valid solutions would be {(1,2), (3,4)}, {(1,3), (4,4)}, {(1,4)}, etc. As each set of bins has a single optimal cost, we can examine this as a shortest path problem.

To see this, we will create a graph as follows: Let us treat each bin as a node in the graph and add a single starting dummy node 0. Let each minimum cost solution for a combined bin set (a, b) be $C(a, b)$, and let that be the cost on the arc $(a\text{-}1, b)$ in the graph. Then, the shortest path from node 0 to largest node B in this graph will be equivalent to choosing the optimal set of combined bin sets, such that all bins must be included. Note that this is not just a Shortest Path problem; it is equivalent to the even simpler Shortest Path on a directed acyclic graph (DAG) problem. See Figure 5-1.
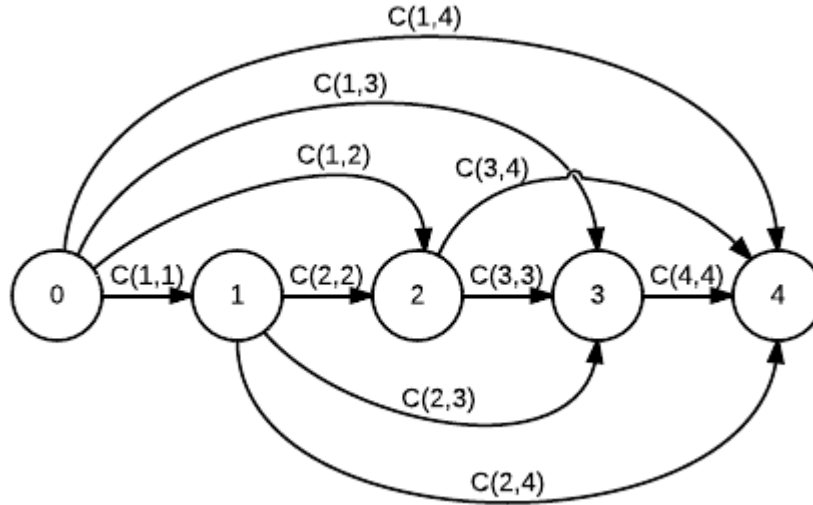

Figure 5-1. Shortest Path Model for a Four-Bin Demand Value Distribution

Then, by examining which arcs have been included in the optimal shortest path solution, we can see which bins should be combined and what strategy each set of bins should employ in a total optimal solution for that retailer. This reduction is noted in Chakravarty et al. (1982).

Note that if we were to not make the assumption that only consecutive bins should be combined, this problem would become substantially more complicated. We would have to solve

the optimal strategy sub-problem for each set of bins where any bin can be included in or excluded from any sub-problem, i.e. 2^B - 1 possible sets. Additionally, to find the optimal combination of these sets, it would be equivalent to a weighted set cover problem, which is well known to be NP-hard. Using the consecutive bins assumption, we have only $O(B^2)$ optimal strategies to run, and the subsequent combination of bins problem is equivalent to a Shortest Path on a DAG problem. This will run in $O(m)$ time where m is the number of arcs $= O(B^2)$. The consecutive bins assumption makes this problem tractable, even for retail importers with a large number of volume bins to consider.

There may be some retail importers that have other operational considerations, such as having a fixed cost to employ each separate strategy, or being limited to a certain number of strategies. We can deal with both of these operational considerations as extensions of the shortest path problem. For the fixed cost per strategy issue, we can simply add that fixed cost to each arc as defined in the shortest path problem. For the limit on multiple strategies, we can modify the normal Shortest Path on a DAG problem such that it keeps the total number of strategies in memory, and disallows any paths including more arcs than the set limit. Neither of these modifications alters the complexity of the algorithm. If a retailer has something like a soft cap on the number of strategies, and would prefer to see all best sets of strategies (i.e. best single strategy, best set of two strategies, best set of three strategies, etc.), we can run the modified shortest path for each possible limit. This would increase the complexity to $O(B^3)$, which is still reasonable for the expected number of bins and available strategies for any given retailer.

5.2. Consecutive Partitions Proof

Given a reasonable set of assumptions, the consecutive bins shortest path solution is in fact provably optimal. This result is based on conditions given in Chakravarty et al. (1985). We will now lay out these assumptions. First, we will assume that the amounts of capital tied up in a unit of stock in different segments of the supply chain are linearly related. That is, we will define a single V value, and assume that $V^S = V \cdot k_S$, $V^N = V \cdot k_N$, and $V^R = V \cdot k_R$ for some constants k_S, k_N, and k_R.

Next, we will define how we generate σ_n, the standard deviation of sales distributed from RDC n. Given a known chain level MAPE value E, we assume that the chain demand is a normal random variable with mean D and standard deviation $\sigma^D = 1.25E \cdot D$. We also have non-identical RDCs underlying that chain, each with known mean demand D_n. We will now make two additional assumptions. First, we assume that the demand for each RDC is also normally distributed. Second, we assume that each RDC has identical MAPE $\overline{E}$. Given the first, we know that the total demand normal random variable is the sum of normals. Thus, the variance of the chain demand is the sum of the variances of the RDC demands. That is, $\left(\sigma^D\right)^2 = \sum_n \left[(\sigma_n)^2\right]$. Given the second, we know that $\sigma_n = 1.25\overline{E} \cdot D_n \to \sigma_n \approx D_n$. Thus, we will let $\sigma_n = xD_n$.

$$\left(\sigma^D\right)^2 = \sum_n \left[(\sigma_n)^2\right] \to \left(\sigma^D\right)^2 = \sum_n \left[(xD_n)^2\right] \to x^2 = \frac{\left(\sigma^D\right)^2}{\sum_n \left[(D_n)^2\right]} \to x = \frac{\sigma^D}{\sqrt{\sum_n \left[(D_n)^2\right]}}$$

$$\sigma_n = D_n \frac{\sigma^D}{\sqrt{\sum_v \left[(D_v)^2\right]}} = \frac{D_n}{D} \frac{\sigma^D}{\sqrt{\sum_v \left[\left(\frac{D_v}{D}\right)^2\right]}} = \frac{D_n}{D} \frac{1.25E \cdot D}{\sqrt{\sum_v \left[\left(\frac{D_v}{D}\right)^2\right]}} \tag{12}$$

Note that the assumption that each RDC has identical MAPE may not be realistic. For an RDC with lower demand, one would expect that it would have a higher percentage error, and vice versa. However, if the RDCs are close to identical or serve a similar number of stores, this assumption will be reasonable.

Lastly, we will assume that all data in each sub-problem remains identical, except for the valuation variable V, inventory holding cost rate r, and the total demand D at that valuation. We will also assume that the proportion of demand required at each RDC $D_n^p = \frac{D_n}{D}$ remains identical in each sub-problem. We can now re-write the total cost objective function as follows:

$$
\begin{aligned}
&D \sum_m \sum_n \sum_i \left((C_m^S + C_{m,n,i}^N)\delta_{m,n,i} D_n^p\right) \\
&+ (k_S)(VrD)\sum_m \sum_n \sum_i \left(L_m^S \delta_{m,n,i} D_n^p\right) + (k_N)(VrD)\sum_m \sum_n \sum_i \left(L_{m,n,i}^N \delta_{m,n,i} D_n^p\right) \\
&+ (k_R)(VrD)(z)\sum_m \sum_n \sum_{i\in DIR} \delta_{m,n,i}\left[L^A\left(1.25E \cdot D_n^p\right)^2 + \frac{\left(1.25E \cdot D_n^p\right)^2}{\sum_v \left[D_v^{p\,2}\right]}\left(L_m^M + L_{m,n,i}^N + R\right) \right.\\
&\left.\qquad\qquad\qquad\qquad + D_n^{p\,2}\left((\sigma_m^M)^2 + (\sigma_{m,n,i}^N)^2\right)\right]^{1/2} \\
&+ (k_R)(VrD)(z)\sum_m \sum_n \sum_{i\in TL} \delta_{m,n,i}\left[L^A\left(1.25E \cdot D_n^p\right)^2 + \frac{\left(1.25E \cdot D_n^p\right)^2}{\sum_v \left[D_v^{p\,2}\right]}\frac{\sum_{v\in\Omega_m}\left[D_v^{p\,2}\right]}{\left(\sum_{v\in\Omega_m}D_v^p\right)^2}L_m^M \right.\\
&\qquad\qquad\qquad\qquad + \frac{\left(1.25E \cdot D_n^p\right)^2}{\sum_v \left[D_v^{p\,2}\right]}\left(L_{m,n,i}^N + R\right) \\
&\left.\qquad\qquad\qquad\qquad + D_n^{p\,2}\left(\frac{\sum_{v\in\Omega_m}D_v^{p\,2}}{\left(\sum_{v\in\Omega_m}D_v^p\right)^2}(\sigma_m^M)^2 + (\sigma_{m,n,i}^N)^2\right)\right]^{1/2}
\end{aligned}
\tag{13}
$$

Although this seems to be an extremely complicated form, it is useful for our purposes here, as we note that the values V, r, and D are found solely in the outer coefficients of the five terms: transportation cost, across-the-water pipeline inventory cost, landside pipeline inventory cost, direct strategy safety stock cost, and trans-load strategy safety stock cost respectively. Recall that we have defined the problem such that the only variables that will vary between sub-problems are those three. All other parameters, including transportation rates, average and

standard deviations of lead times, and proportions of demand at each RDC, will be equivalent in all sub-problems.

According to Chakravarty et al. (1985), the following is a sufficient set of conditions to conclude that consecutive partitions will be optimal:

1) We can define values $\alpha_j > 0$ and $\beta_j > 0$ for each ordered sub-problem j such that $\dfrac{\alpha_1}{\beta_1} \leq \ldots \leq \dfrac{\alpha_B}{\beta_B}$;

2) For any given set of sub-problems P, $\alpha_P = \displaystyle\sum_{j \in P} \alpha_j, \beta_P = \displaystyle\sum_{j \in P} \beta_j$;

3) We can define the total problem cost as the sum of a function of α_P and β_P for each set of sub-problems; i.e. for a set of sets of sub-problems that completely covers all sub-problems $g_L(P_1, \ldots, P_L) = \displaystyle\sum_{l=1}^{L} h(\alpha_{P_l}, \beta_{P_l})$; and

4) $h(\alpha_{P_l}, \beta_{P_l})$ is concave in all of its α_{P_l} and β_{P_l} variables.

If we define $\alpha_j = V_j r_j D_j$ and $\beta_j = D_j$, then we will be ordering these sub-problems by $\dfrac{\alpha_j}{\beta_j} = V_j r_j = \rho_j$ as before, and we can see that in our defined problem, the weighted averages of inventory holding cost values as weighted by demand fit all of the above conditions. In fact, in this case, the total cost function (13) is actually linear in the α_{P_l} and β_{P_l} variables. Thus, we have shown that the consecutive bins shortest path solution is optimal under the assumption that only variables V, r, and D vary between sub-problems.

Note that this consecutive bins shortest path approach is not limited to using the provided heuristic to find the total cost for an optimal single strategy for a set of value bins. The arc costs can be generated by any optimization procedure that provides optimal or near-optimal total transportation + pipeline inventory + safety stock costs for a single strategy retailer.

5.3. Simulation Results

We have thus extended the single retail importer problem to consider employing multiple strategies across the importer's product portfolio. Each retail importer utilizing this method must have a value distribution defined as a set of value bins, each bin having a pre-specified declared value holding rate and demand volume. By treating sets of consecutive bins as if each set was a separate retail importer in the original problem, and utilizing a Shortest Path algorithm to cover all bins, we can find the optimal set of strategies and lowest total cost for that retail importer.

Based on the data from the case study retailer as well as on Customs data collected on all Asia – USA importers, an approximate value distribution with nine bins was generated as below. The weighted mean declared value of the goods in this distribution is $25 per cubic foot.
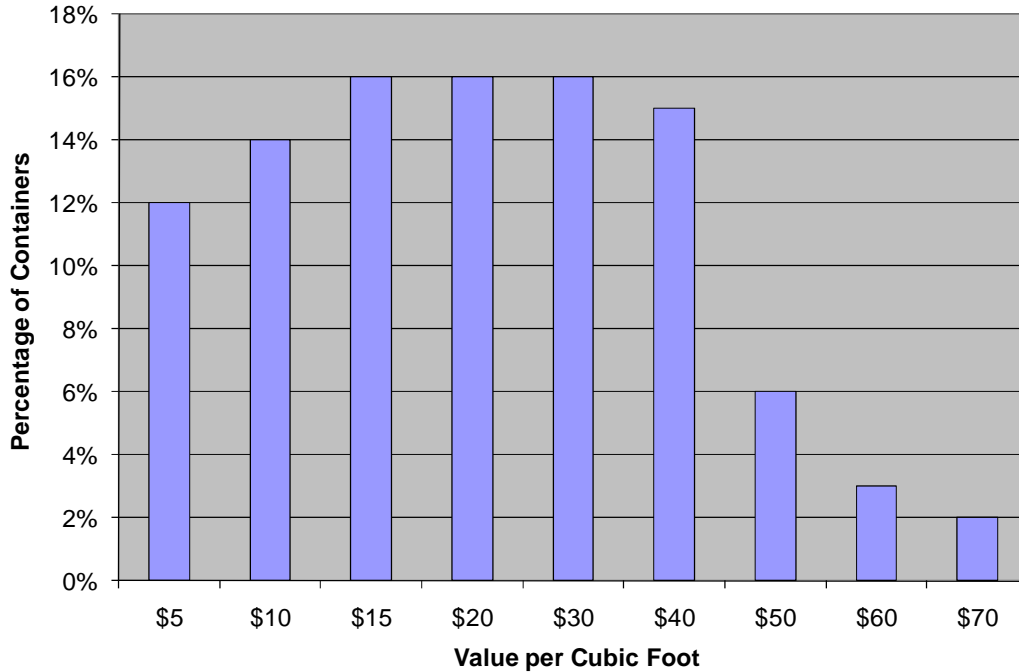
Figure 5-2. Histogram of Goods Valuation Distribution for the Case Study Retailer.

Although not all imported containers destined for a specific RDC will always use the same port of entry, it will be a reasonable approximation to assume this. Thus, we can approximate the case study retailer's current overall supply chain strategy and its associated costs. (See Appendix B.) We can then examine the cost differences between its (approximated) current strategy and the optimal set of strategies as found by our model.

Table 5-1. Cost Reduction Using the Heuristic & Shortest Path Multi-Strategy Model for the Case Study Retailer.

Number of Strategies Allowed	Cost Reduction Using Multi-Strategy & Heuristic	Selected Strategies Using Multi-Strategy & Heuristic (Volume Employing Each Strategy)
1	2.16%	TL-2-WC (100%)
2	2.83%	Direct (26%), TL-2-WC (74%)
3	2.95%	Direct (26%), TL-3-Sav (48%), TL-LA (26%)
4	3.0396%	Direct (26%), TL-3-Sav (48%), TL-2-WC (31%), TL-LA (11%)
5	3.0404%	Direct (26%), TL-3-Sav (48%), TL-2-WC (31%), TL-LA (11%)
6	3.0406%	Direct (26%), TL-3-Sav (48%), TL-2-WC (31%), TL-LA (11%)

Allowing more than six strategies does not change the minimal cost solution and optimal set of strategies in this case. Note that the optimal solutions for the cases of up to four strategies allowed, up to five strategies allowed, and up to six strategies allowed actually send the same volumes via the same strategies. However, underlying the strategy selection is the allocation of the particular RDC volumes to particular ports. When these underlying allocations differ for

24

different bins of goods, the strategies are considered to be different. Thus, using these given transportation rate and transit time data, there is a benefit to allowing some merchandise to use the same strategy but with slightly altered port-RDC allocations.

To be assured that this is a robust result, we introduced a second potential value distribution for the retailer's imported goods. This distribution introduces more low- and high-value goods and reduces the volume of medium-value goods, while keeping the weighted mean of the goods value the same.
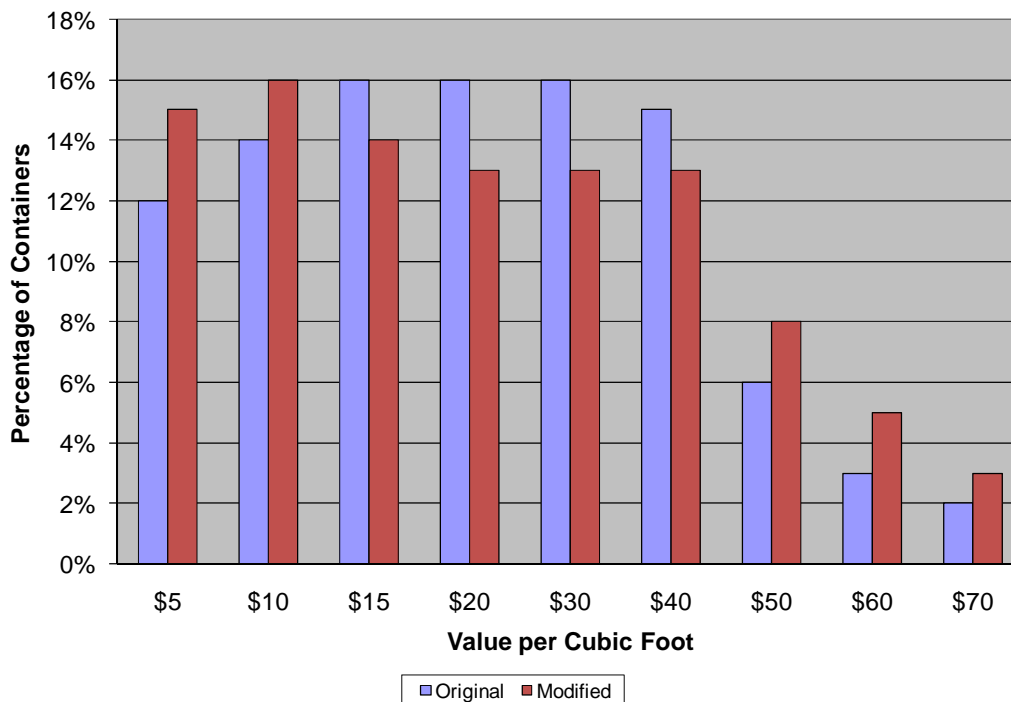
Figure 5-3. Histogram of Modified Goods Valuation Distribution for the Case Study Retailer.

Using this modified value distribution, we find that there is an even greater reduction in cost afforded this retailer by employing multiple import strategies.

Table 5-2. Cost Reduction Using the Heuristic & Shortest Path Multi-Strategy Model
for the Case Study Retailer Under the Modified Goods Valuation Distribution.

Number of Strategies Allowed	Cost Reduction Using Multi-Strategy & Heuristic	Selected Strategies Using Multi-Strategy & Heuristic (Volume Employing Each Strategy)
1	2.21%	TL-2-WC (100%)
2	3.00%	Direct (31%), TL-2-WC (69%)
3	3.19%	Direct (31%), TL-3-Sav (40%), TL-LA (29%)
4	3.263%	Direct (31%) TL-3-Sav (27%), TL-2-WC (26%), TL-LA (16%)
5	3.2639%	Direct (31%) TL-3-Sav (27%), TL-2-WC (26%), TL-LA (16%)
6	3.2641%	Direct (31%) TL-3-Sav (27%), TL-2-WC (26%), TL-LA (16%)

25

The total demand for our case study retailer is approximately 350,000 TEUs per year and has a total supply chain cost of approximately $1.4 billion per year. Here we see that by using these optimal strategies, they can save between $30 million and $47 million per year, depending on what their true goods valuation distribution is, and depending upon how many supply chain strategies they can operationally handle. There may be additional operational costs associated with increasing the number of strategies that the retailer does handle. This analysis does not take any of these costs into account.

Note also that the large majority of the cost benefit is realized when optimizing to a two-strategy solution. Adding additional strategies reduces the total supply chain cost only marginally. The cost reduction in using the two-strategy solution primarily comes from splitting off the cheap goods that can be handled with a Direct strategy from the more expensive goods that should be handled with a Trans-loading strategy. By finding that single breakpoint for the retailer, we can capture over 90% of the total possible cost reduction based on our optimization heuristic.

6. Less-Than-Container Shipments

The total shipped volume of a set of goods from a particular port to a particular destination RDC will usually not fit exactly into an integer number of containers. As much as a retailer will attempt to balance the number of shipments to minimize this problem, they will often have to make some less-than-container shipments. This can be considered inefficient, as the retailer would be paying the full transportation cost, or a higher than expected portion of that transportation cost to ship a non-full container.

Considering the shipments fulfilling the weekly volume for a given port-RDC combination, this will likely affect only one container, as all but one can be fully packed. To accurately calculate transportation costs for a given port-RDC combination, we can then round up the volume to an integer number of containers. We can take the ratio of the rounded-up integer number of containers to the fractional number, and multiply that by the applicable transportation costs. As the original volume becomes large, the amount added when rounding up will become a smaller proportion of the original amount, so this ratio will clearly become closer to 1. Using this rounding factor, we would be more likely to aggregate more volume into the same strategy, in order to economize on transportation costs.

Let e_i be the total volume that a single container used for transportation mode i can hold, where e_{DIR} is the total volume that a single marine container can hold when i is a Direct shipping strategy, and e_{TL} is the total volume that a single domestic container can hold when i is a Trans-loading strategy. Generate a rounding factor as

$$f_{n,i} = \frac{e_i}{D_n} \left\lceil \frac{D_n}{e_i} \right\rceil \tag{14}$$

This factor only applies to the transportation costs. No matter how much empty space there is in a container, the same amount of inventory will be in transit or held as safety stock. To model the costs for a retailer using less-than-container shipments, we can further modify the updated heuristic from Section 4.7. by replacing all instances of formula (3) with formula (15).

26

$$\sum_m \sum_n \sum_i ((f_{n,DIR} C_m^S + f_{n,i} C_{m,n,i}^N) \delta_{m,n,i} D_n) \qquad (15)$$

Note that now for all strategies, we apply the Direct shipping round-up factor to across-the-water volume for both strategies. For the landside volume, we apply the round-up factor that reflects the actual weekly volume and transportation mode of that particular strategy. For Trans-loading strategies, this is not a perfectly accurate representation of the partial container usage for the across-the-water transportation. Under the heuristic, we know exactly how much volume needs to reach each RDC n. Ideally, for the Trans-loading strategies, we would apply the marine container round-up factor to the total volume coming into a given port. However, at that stage of the heuristic, we do not know how much volume will be entering each port; those volumes are chosen in setting the optimal strategy. Therefore, we cannot apply this ideal round-up factor to the across-the-water transportation costs. We will instead apply the marine container round-up factor to each RDC's volume. This will also better account for those cases where the shipper at the Asian origin cannot perfectly consolidate shipments of disparate goods.

It is important to note that by introducing this round-up factor, we can no longer say that a consecutive bins shortest path solution is optimal. The total transportation cost, i.e. the first term from the objective function (13), can be written as

$$\sum_m \sum_n \sum_i \left(\left(f_{n,DIR} C_m^S + f_{n,i} C_{m,n,i}^N \right) \delta_{m,n,i} D_n \right) =$$

$$\sum_m \sum_n \sum_i \left(\left(e_{DIR} \left\lceil \frac{D \cdot D_n^p}{e_{DIR}} \right\rceil C_m^S + e_i \left\lceil \frac{D \cdot D_n^p}{e_i} \right\rceil C_{m,n,i}^N \right) \delta_{m,n,i} \right) \qquad (16)$$

This is clearly no longer concave in D, due to the ceiling function in the round-up factor.

In fact, it is quite simple to construct a pathological case such that the optimal result utilizes the same strategy in non-consecutive bins. For example, we can generate such a case as follows. Develop a value distribution of three bins. Assume that in the heuristic without the less-than-container round-up factor, the optimal solution would set the strategy employed by the volume in bin 1 to s_1, and the strategy employed by the volume in both bins 2 and 3 to s_2. Let the demand for all RDCs in bin 1 be large, and such that the volumes are very close to an integer number of containers. That is, $f_1 > 1$, but is very close to 1. Let the demand for all RDCs in bin 2 be large, and such that the volumes exactly fill containers, i.e. $f_2 = 1$. Finally, let the demand in bin 3 be very small, and such that all RDCs will need a very large round-up factor to fill a single container, i.e. $f_3 \gg 1$. However, we will also say that if the demands in bins 1 and 3 were pooled, then those combined volumes would exactly fill containers, i.e. $f_{1+3} = 1$. It is easy to see that a set of transportation rate, lead time, etc. parameters could be generated such that the optimal solution would pool bins 1 and 3 and they would utilize strategy s_1, while bin 2 would utilize s_2. That is, the increase in costs for using a sub-optimal strategy for the small volume in bin 3 would be less than the increase in costs that would result from having the less-than-container round-up factors applied to both the volume in bin 1 under strategy s_1 and the combined volume from bins 2 and 3 under strategy s_2.

When some bins have very low volumes, those bins might be most efficiently pooled with some other bin that is not a neighbor. However, given reasonably large volumes in every bin, the

consecutive partitions shortest path solution will likely provide near-optimal results. As such, we will continue to use the shortest path solution for our study of the multi-strategy optimal solution even when including the less-than-container round-up factor in the transportation costs.

We subsequently analyzed the data from the case study retailer using this rounding factor to account for less-than-container shipments. We again examined the cost differences between their approximated current strategy and the optimal set of strategies:

Table 6-1. Cost Reduction Using the Heuristic Modified for Less-than-Container Shipments with the Shortest Path Multi-Strategy Model for the Case Study Retailer

Number of Strategies Allowed	Cost Reduction Using Multi-Strategy & Heuristic	Selected Strategies Using Multi-Strategy & Heuristic (Volume Employing Each Strategy)
1	2.15%	TL-2-WC (100%)
2	2.61%	Direct (26%), TL-2-WC (74%)

The two-strategy solution given is optimal under this modified heuristic, even when more than two strategies are allowed. This is an expected change, as the modified transportation cost formula implies that aggregating more volume into the same strategy would generate cost savings. We note that the cost reduction is not as great in this modified heuristic. This is also an expected result, as there is now an additional penalty for breaking the goods up into separate strategies. Nonetheless, the cost savings for the two-strategy solution are still impressive for a high-volume importer; the case study retail importer would save an additional $6.5 million per year over the best single strategy solution. (This compares to a savings of $9.4 million calculated in Table 5-1 for the case of all full-container shipments.)

7. Breakpoint Analysis

Using the less-than-container analysis as outlined in the previous section, we can examine the sensitivity of the specific optimal strategy to variation in a number of parameters. By running an exhaustive set of simulations, we can approximate the breakpoints between the various strategies. It is useful to note that if we do not use the less-than-container version of the analysis, the optimal strategy would not be affected by the retailer's importing volume per year. If we do allow fractional container loads with no cost penalties, the importing demand can always be split as necessary without affecting the cost per TEU. As the cost per TEU for a given strategy would remain the same for all retailers at a declared good value, the optimal strategy will remain the same for all importing volumes.

We have three sets of parameters for which we will conduct breakpoint analysis:

1) Transportation rates, transit times, and RDC demand distributions as per the average United States retailer according to Customs data, as used in the original case studies produced for the Ports of Los Angeles and Long Beach from Leachman (2008).

2) Transportation rates, transit times, and RDC demand distributions as provided by our top-5 national big-box case study retailer.

3) Transportation rates and transit times as provided by our case study retailer, but applied to RDC demand distributions as per the average United States retailer according to Customs data.

These three sets of parameters allow us to test the optimal strategies for both an average retailer as well as an actual top-5 retailer that is able to leverage its economies of scale and large presence to potentially receive favorable transportation rates. The third scenario is put in place to attempt to reduce the effect of our case study retailer's infrastructure and geographically varying market shares. This retailer has a particularly strong presence in the South and a weaker presence in the Northeast. As such, by setting the RDC demand distribution to look more like the average US retailer, we can attempt to find the optimal importing strategy for a "generic top-5" retailer. This set of parameters cannot perfectly approximate a "generic top-5" retailer, as the case study retailer's regional presence is also reflected in the provided transportation rates and transit times, but we may be able to capture some interesting differences.

7.1. Single Strategy Breakpoints

First, we will examine the cases where the retailer can only utilize a single importing strategy. For each set of parameters described above, we will test a variety of declared values of the goods, from cheap goods valued at $5 per cubic foot to expensive goods valued at $70 per cubic foot. We will also test a variety of retailer importing volumes, from a very small retailer importing only 1,000 TEUs per year to a "Walmart-sized" retailer importing 1,000,000 TEUs per year. Each combination of goods declared value and yearly importing volume will have its optimal supply chain strategy. We will examine where those optimal strategies change.

7.1.1. Single Strategy – Average US Retailer

Here we show a chart describing the optimal supply chain strategy under the Average US Retailer set of parameters. As we would expect, Direct shipping is prevalent at low goods valuations, Trans-loading becomes viable at higher goods valuations, and we trans-load at fewer and fewer ports as the goods valuations increase. All charts below show the importing volume per year in TEUs on a logarithmic axis, as it is more suited to an analysis of strategy shifts at different magnitudes of volume.
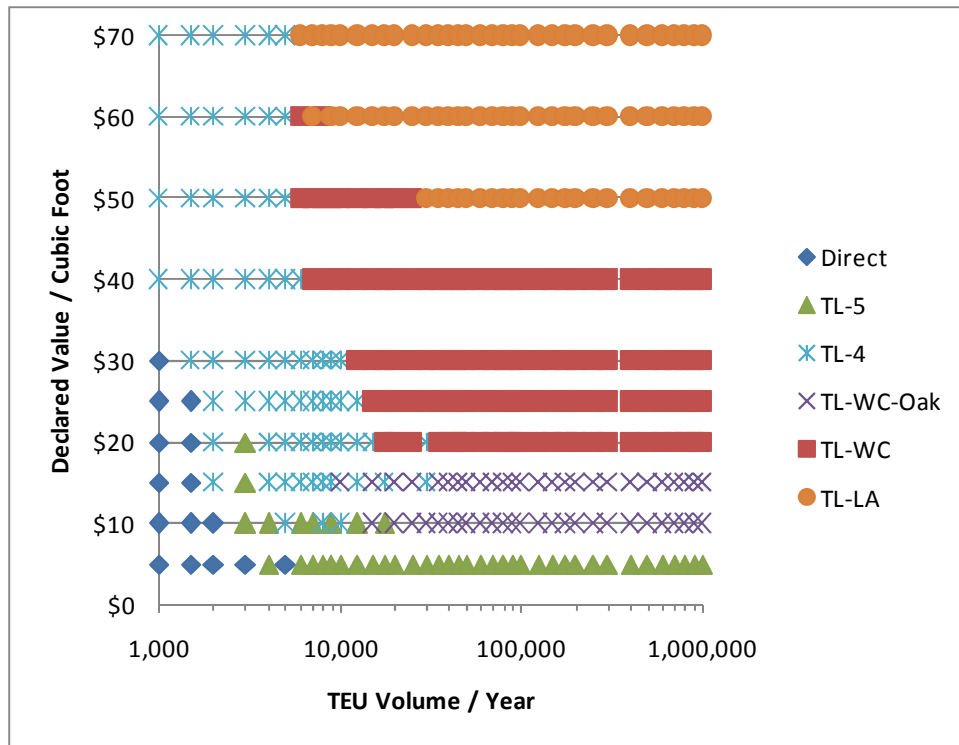
Figure 7-1. Optimal Importing Strategy for Various Importing Volumes and
Various Declared Goods Values for an Average US Retailer.

We note many interesting observations about this chart. First, we see that a Direct strategy is used, but only at the lowest importing volumes and goods valuations. As the marine containers are smaller than the domestic containers used for Trans-loading, the less-than-container round-up factor will affect Direct shipping less. At low importing volumes, the round-up factor for domestic containers applied to over-land transportation cost to each RDC is comparatively large. For the smallest volume retailers, the cost benefit by using the round-up factor for marine containers only is enough to limit the optimal strategy to Direct shipping, even at medium to high goods valuation. As the importing volume increases, the goods valuation necessary to generate a Trans-loading shipping strategy reduces, until only the cheapest $5 per cubic foot goods require Direct shipping. Once a retailer has an importing volume larger than 5,000 TEUs per year, Direct shipping is no longer the optimal strategy, no matter the goods valuation.

At the highest volumes, we would expect the container round-up factor to have the least effect, and thus we would expect that the strategies selected at those highest volumes would be equivalent to the selected strategies had we not used the partial container analysis round-up factors. At the largest simulated volume, we see that the optimal strategies are TL-5 (Trans-loading at LA-LB, Seattle, Houston, Savannah, and NY-NJ) for $5 per cubic foot goods, TL-WC-Oak (Trans-loading at LA-LB, Seattle, and Oakland) for $10-$15 goods, TL-WC (Trans-loading at LA-LB and Seattle) for $20-$40 goods, and TL-LA (Trans-loading at LA-LB only) for goods with a valuation greater than $50.

We see a pattern for each subsequent Trans-loading strategy similar to that of the Direct strategy. There are "bands" associated with each Trans-loading strategy, with higher importing

volumes and low goods valuations utilizing the same strategies as those with low importing volumes and high goods valuations. While TL-5 is only optimal for $5 at the highest volumes, it becomes optimal for some cases of more expensive goods as the imported volume is reduced. This again has to do with the round-up factor used in the analysis. The TL-4 strategy (Trans-load at LA-LB, Seattle, Savannah, and NY-NJ) is never used at the largest volumes, but it is a prevalent optimal strategy at lower volumes.

This largely has to do with the round-up factors, and specifically how they interact with the Direct Dray transportation method. At the low volumes, the domestic container round-up factor is proportionally larger than the marine container round-up factor. However, even under Trans-loading strategies, the Direct Dray transportation method uses the marine container round-up factor for over-land transportation. Thus, at low volumes there is a benefit to providing access to the Direct Dray method for additional ports. Once the importer can use those Direct Drays from ports to nearby RDCs, it encourages trans-loading out of those ports. As the volumes increase, the benefit from using the marine container round-up factor for the Direct Dray paths stops outweighing the benefit of risk pooling at fewer locations, and we see the optimal strategies move to fewer ports. We note that this explains the changeover from the TL-4 strategy to the TL-WC-Oak strategy in that approximate 3-4 port "band", seen approximately at 10,000 TEUs per year with a declared good value of $15.

It is also worth noting that the "bands," i.e., the regions described by each optimal strategy, are not exact. Sometimes, as the volume or goods valuation varies in a small region, the optimal strategy will switch back and forth a few times before settling down to a single optimal strategy in that region. For example, note the area at $15 goods between 10,000 and 50,000 TEUs per year. Here, there is ambiguity as to whether the optimal strategy is TL-4 or TL-WC-Oak. These strategies have similar cost structures and similar risk pooling and are thus fairly interchangeable in this region. The minor differences can likely be attributed to the changing partial container round-up factors. As the volume increases, the round-up factor to each RDC will decrease until it hits 1 (as the container fills exactly), after which it will jump back to a number greater than 1. The "ambiguous" regions described above are likely due to these jumps in the round-up factor happening at different volumes for different RDCs.

We can also examine how the total supply chain cost per TEU changes for the different importing volumes and goods valuations.
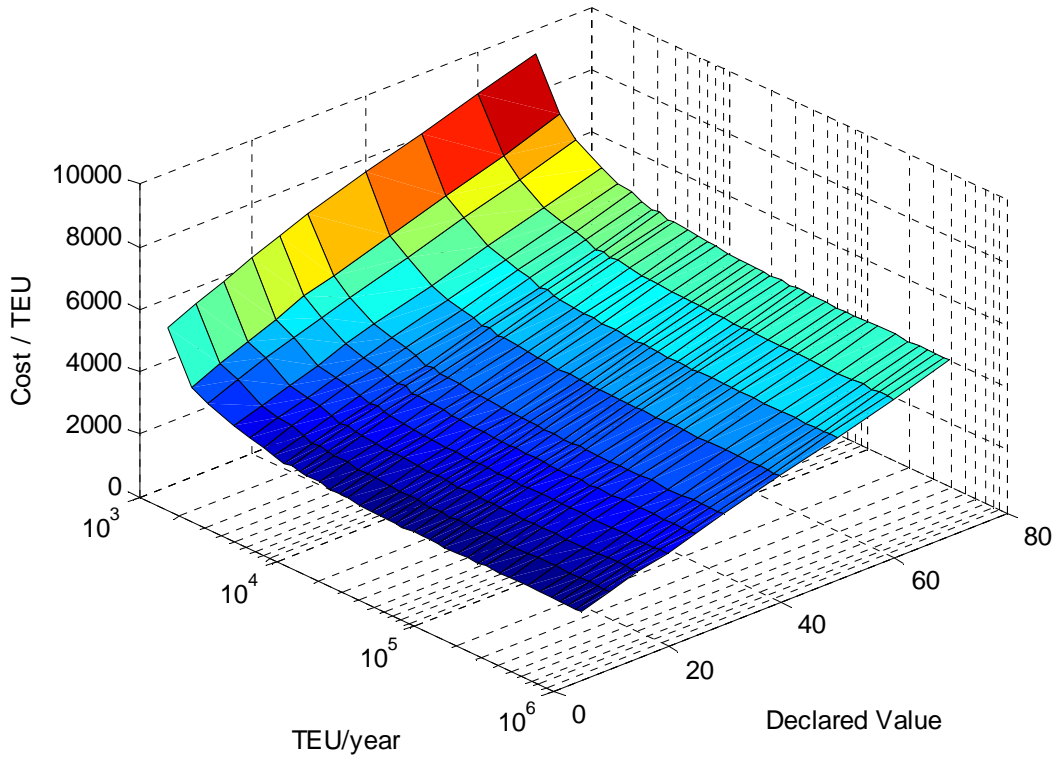
Figure 7-2. Cost per TEU for Different Importing Volumes and
Declared Goods Values for an Average US Retailer.

Here we note that for a given goods valuation, as the importing volume increases from the lowest volumes, the average cost per TEU drops very drastically and very quickly converges to some stable average cost. Additionally, we find that for a given importing volume, the cost per TEU increases sub-linearly with the goods valuation. Based on formula (13), we note that the declared goods value (*Vr*) is a linear factor in the total cost function. Thus, within a range utilizing the same importing strategy and port-RDC allocations, this cost will increase exactly linearly. When the optimal strategy changes at a particular goods valuation the cost per TEU can only increase sub-linearly. If the model recommended a different strategy that produced a cost per TEU that increased super-linearly in the declared goods value, the model could have instead selected the same strategy as for the lower importing volume and increased the cost linearly. Therefore, for a given importing volume, switching strategies must produce a cost per TEU that increases either linearly or sub-linearly in declared goods value.

7.1.2. Single Strategy – Top-5 Retailer

Here we show the optimal strategies for the different importing volumes and goods valuations for the transportation cost and RDC distribution for our case study top-5 retailer.
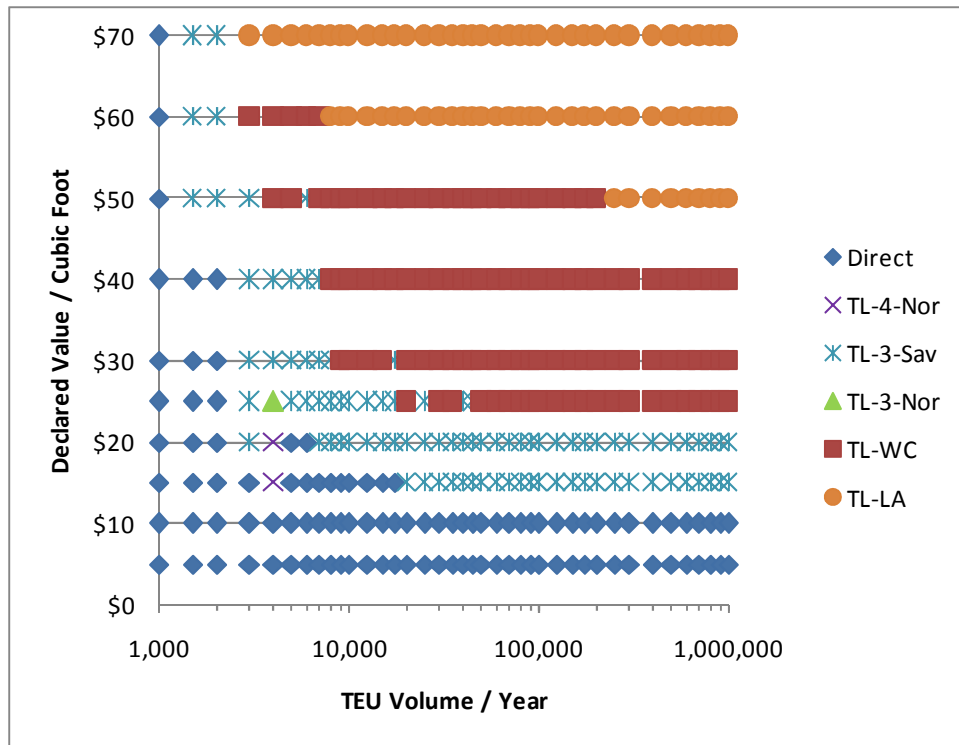
Figure 7-3. Optimal Importing Strategy for Different Importing Volumes and
Declared Good Values for the Case Study Top-5 US Retailer.

There are some substantial differences between this chart and the one for the average US retailer. First we note that the Direct shipping strategy is much more prevalent. This would suggest that this retailer has received very favorable Direct shipping rates from certain logistics providers. Such reduced rates would incentivize the retailer to use the Direct shipping strategy even at high volumes for the cheapest goods, as well as at high goods valuation for very small volumes.

We now see that the optimal strategies at the highest volumes (i.e. ignoring partial container round-up factors) are Direct shipping for $5-$10 per cubic foot goods, TL-3-Sav (Trans-loading at LA-LB, Seattle, and Savannah) for goods valued between $15-$20, TL-WC for goods valued between $25-$40, and TL-LA for goods valued at $50 or above.

The TL-3-Sav strategy has basically replaced the multi-port "band" that we saw for the average US retailer scenario, abandoning any usage of the NY-NJ port. Another difference is for goods valued around $50. We note that in the average retailer case, the Trans-load at LA-LB only strategy becomes optimal above about 30,000 TEUs per year. However, for the case study retailer, the TL-LA strategy becomes optimal only above 250,000 TEUs. Both of these differences can largely be attributed to the infrastructure of the case study retailer, and the fact that their operational strategies are centered on the Southern and Midwest regions of the United States, and not in the Northeast or West Coast.
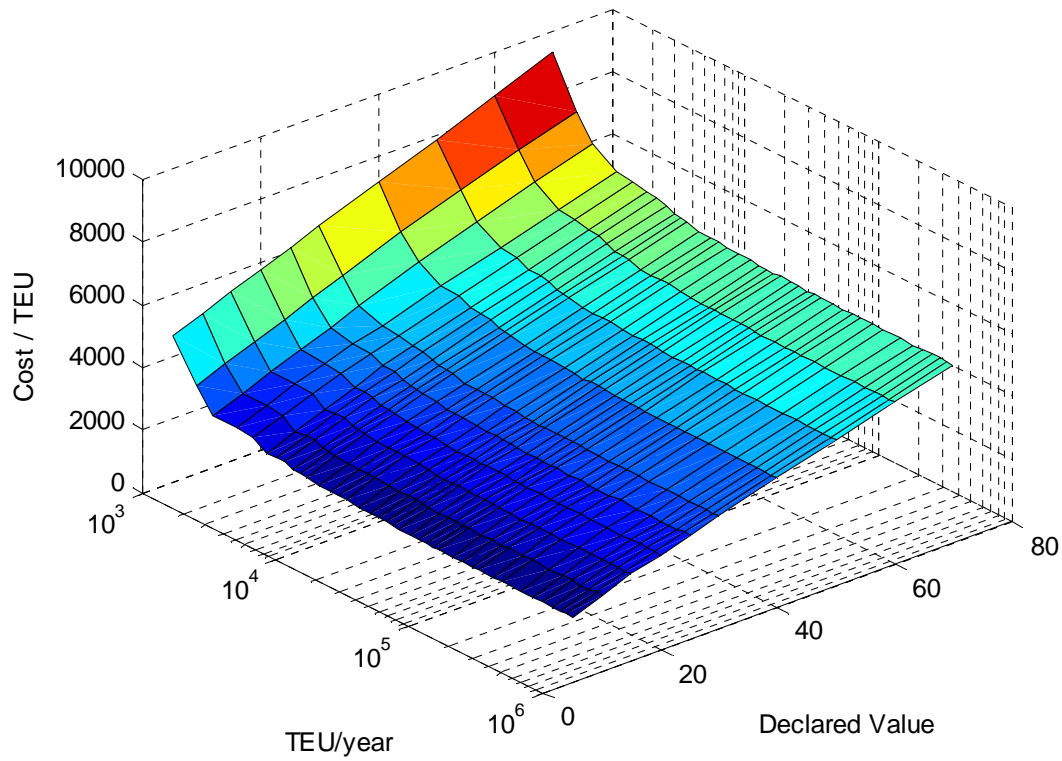
Figure 7-4. Cost per TEU for Different Importing Volumes and Declared Good Values
for the Case Study Top-5 US Retailer.

7.1.3. Single Strategy – Top-5 Retailer, Average US Retailer RDC Demand Distribution

Here we show the optimal strategies for the different importing volumes and good valuations for the transportation cost for our case study top-5 retailer, using the approximated RDC distribution of the average United States retailer.
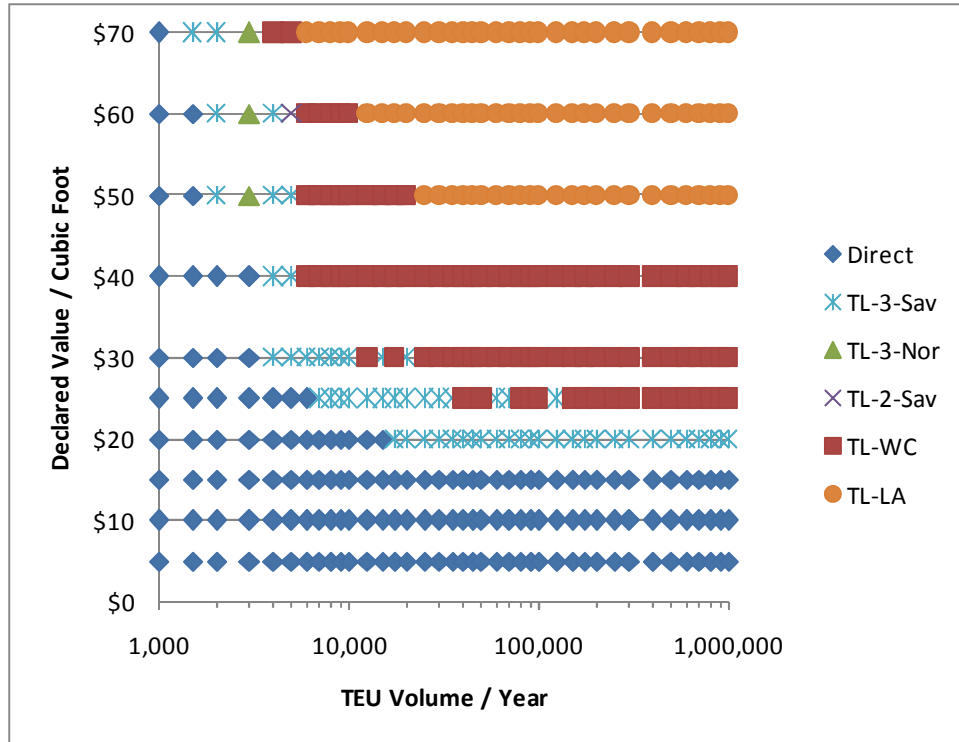
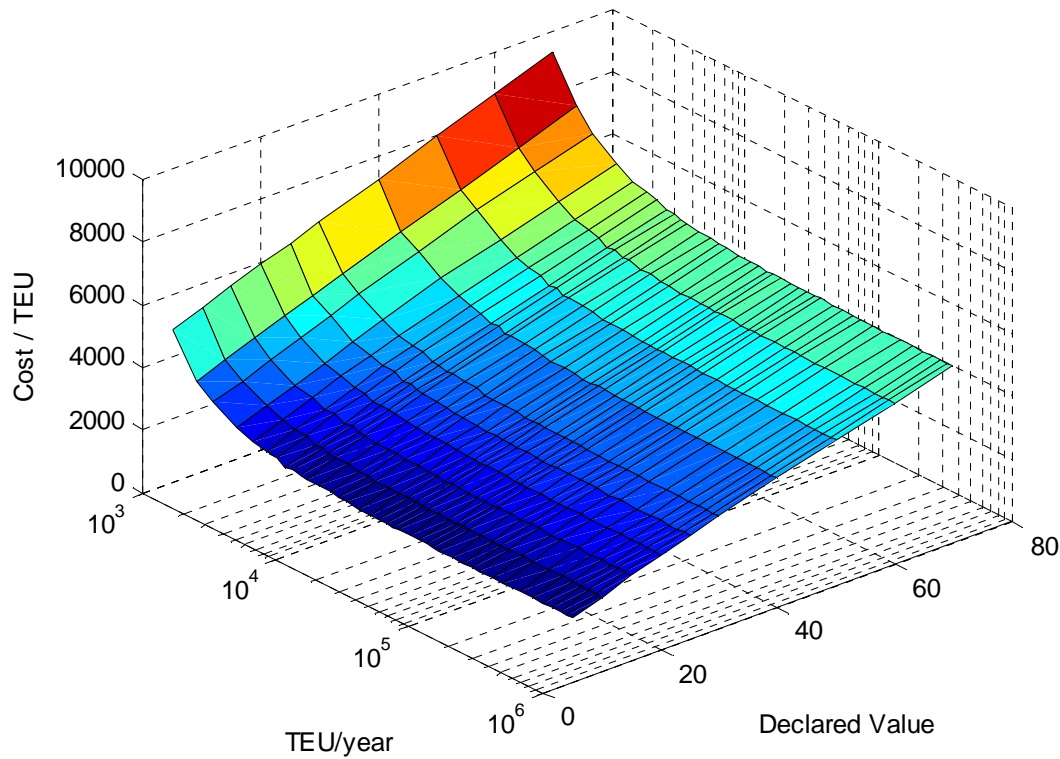Figure 7-5. Optimal Importing Strategy for Different Importing Volumes and Declared Good Values for the Transportation Parameters of Case Study Top-5 US Retailer Using the Average Retailer RDC Distribution.

This chart has a very similar structure to the previous scenario. The Direct shipping strategy has become even more prevalent, though the different between the second scenario and this scenario is much smaller than the difference between the first scenario and the second. Additionally, we note that the TL-LA strategy has returned to being optimal for the $50 per cubic foot goods for volumes between about 30,000 and 250,000 TEUs per year. This validates the claim made above that this change mostly has to do with the specific RDC demand distribution of this case study retailer.

Figure 7-6. Cost per TEU for Different Importing Volumes and Declared Goods Values for the Transportation Parameters of the Case Study Top-5 US Retailer Using the Average Retailer RDC Distribution.

While we are testing these transportation rate and RDC distribution parameters for many importing volumes and goods valuations, it may not be entirely reasonable to expect that a retailer at any particular intersection of volume and values can use these particular parameters. As mentioned previously, the top-5 retailer likely has used its leverage to negotiate favorable Direct shipping rates, using their economies of scale to justify the lower rates. These rates likely would not be made available to retailers with smaller volumes. Additionally, for retailers having the smallest importing volumes, it is unlikely that they will operate in a manner consistent with the assumptions of this model. First, it is unlikely that such a small retailer will have the infrastructure and scale to operate over 20 RDCs across the United States. It is also unlikely that a small retailer would choose to import goods once a week. It is more likely that these smallest retailers would have fewer RDCs and import once every two weeks or even less often. At the smallest volumes that we're testing, 1,000 TEUs per year, when using the given RDC distribution, the demand for most RDCs is less than one TEU per week. Thus, this model breaks down at these lowest volumes. Nonetheless, it is still informative to examine the breakpoints, as we can see the substantial number of situations where a Trans-loading strategy is optimal, when those strategies are made available to retailers.

7.2. Multiple Strategy Breakpoints

We will now examine a similar set of breakpoints for those retailers that can apply different supply chain strategies to goods with different values in their product portfolio. As in the

36

previous section, we will use the goods valuation distribution as estimated for our case study retailer. As a reminder, this retailer has an average goods valuation of about $25 per cubic foot. For many major retailers, however, trans-Pacific supply chains for their most expensive goods (electronics, etc.) are managed by the Original Equipment Manufacturers (OEMs). That is, the OEMs control the importing strategy of these expensive goods until they arrive at the retailer's RDC. As such, we will also test a distribution that is basically equivalent to that used in the case study, but removing all goods with a valuation of $40 per cubic foot or greater. In this truncated distribution, the mean goods valuation is just under $15 per cubic foot.
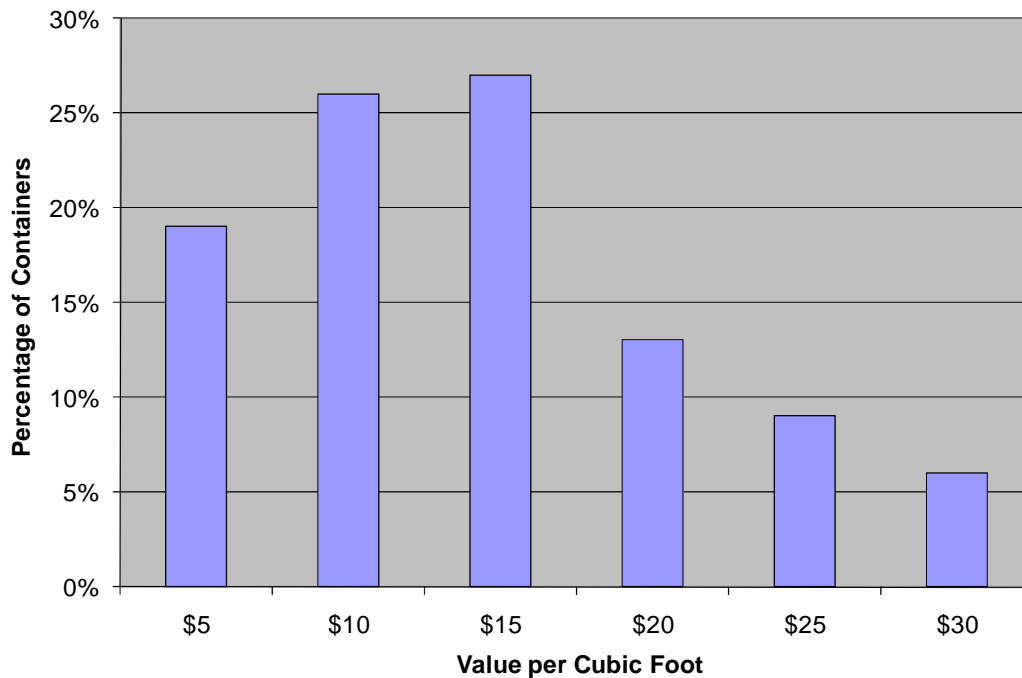
Figure 7-7. Histogram of Truncated Goods Valuation Distribution

Clearly, the goods valuation distribution will have a major effect on the optimal strategy or set of strategies, but this analysis will show that we can use the model to find the importing volume at which it is reasonable to switch strategies or split into multiple strategies. We will not show the exact set of goods that would be recommended to each given strategy, as that would overly complicate these graphs. However, it should be clear that the cheapest goods will be utilizing Direct shipping strategies, slightly more expensive goods will use a multi-port Trans-loading strategy, and as we continue increasing goods valuation we reduce the number of ports until the most expensive goods use the Trans-load only at LA-LB strategy.

7.2.1. Multi-Strategy – Average US Retailer

We will examine a chart that shows the optimal strategy for the retailer at different volumes. This chart will also show the average cost per TEU imported, thus showing how the economies of scale provide an advantage to the larger retailers, specifically in terms of the partial container round-up effect. We will now show hypothetical retailers with import volumes ranging up to a volume that would be approximately equivalent to five times the recent import volume of Walmart, for illustrative purposes.
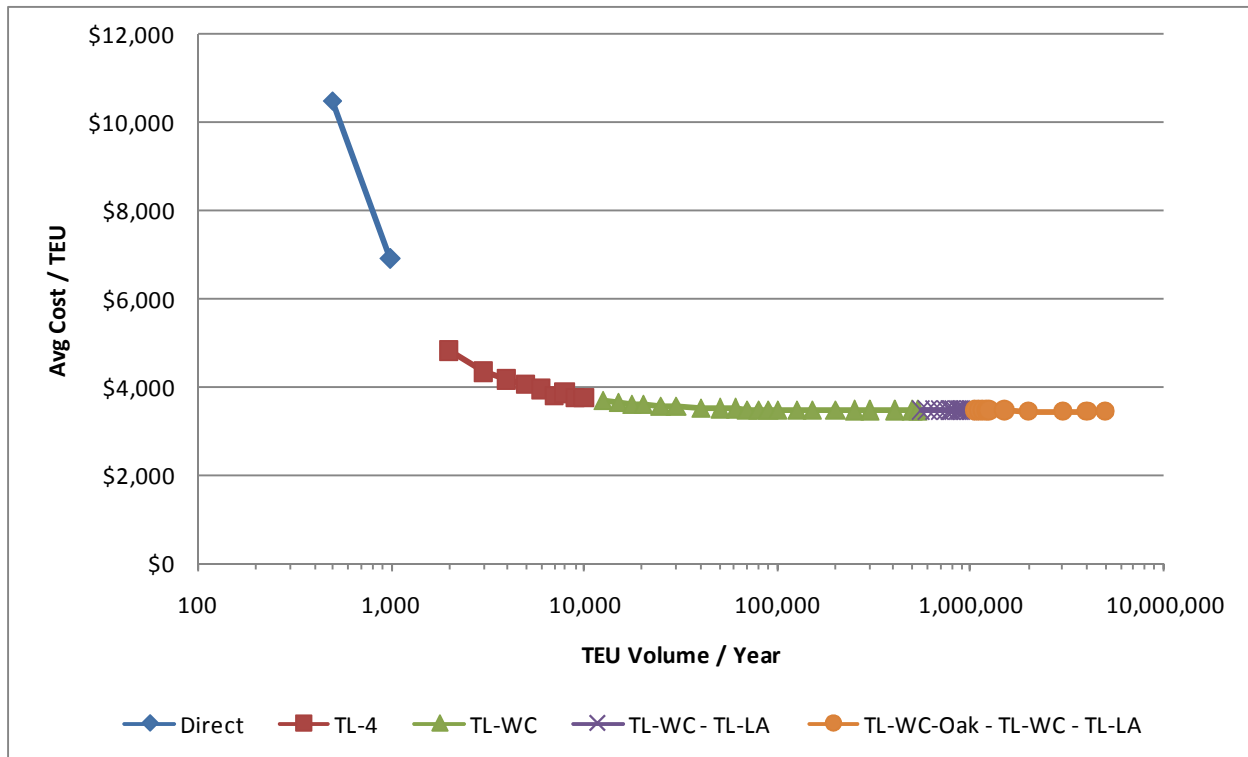
37

Figure 7-8. Average Cost Per TEU and Optimal Strategy for an Average US Retailer with the Capability to Handle Multiple Strategies, All Goods Included

Up to an import volume of approximately 525,000 TEUs per year, our analysis suggests that a single strategy is optimal, matching what we saw from the optimal single strategy for a retailer with a goods valuation of $25 per cubic foot. Between 550,000 and 1,000,000 TEUs per year, the analysis suggests that the retailer should split their goods such that the cheapest goods are Trans-loaded through both LA-LB and Seattle while the most expensive goods are Trans-loaded through LA-LB only. For a retailer importing greater than 1,000,000 TEUs, the analysis recommends a third category, where the cheapest goods are Trans-loaded through an additional port, Oakland. The medium value goods will now use TL-WC. Even at "super-Walmart" levels of volume, this analysis never recommends splitting goods such that four separate strategies are applied. Also, this analysis never recommends the use of Direct shipping in optimal multi-strategies. This is an expected result for this parameter set, as we saw that the single optimal strategy at this volume even for the cheapest goods uses Trans-loading.

At the lowest importing volumes, the average cost per TEU is very high, over $5,000 per TEU. However, it quickly drops off, decreasing to under $4,000 at 6,000 TEUs per year, dropping below $3,600 at 25,000 TEUs per year, and converging to approximately $3,450 as the volume continues to increase.

We would also like to examine how much benefit a retailer of any given volume will gain by utilizing more than one strategy.
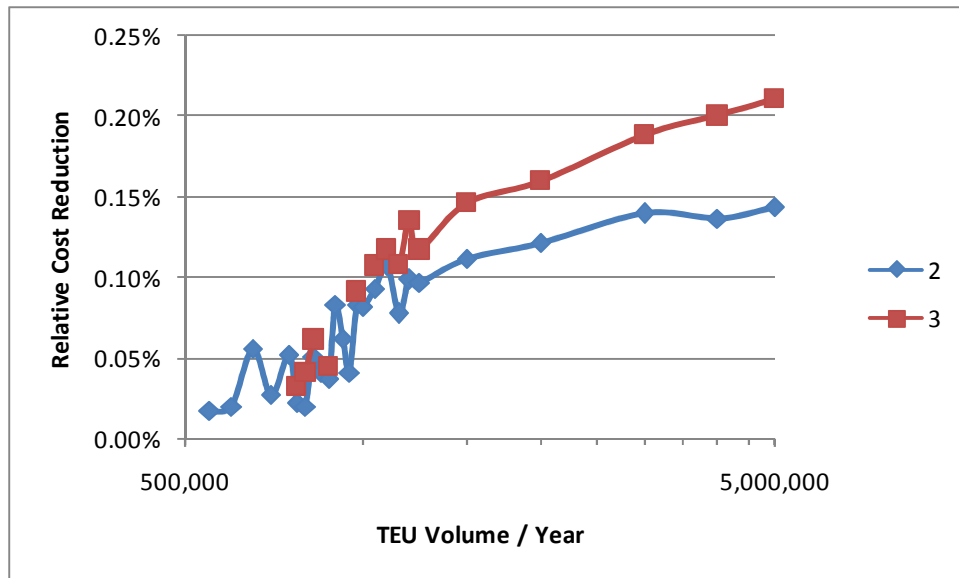
Figure 7-9. Relative Cost Reduction for an Average US Retailer
By Utilizing Multiple Strategies, All Goods Included

Here we see that the relative cost benefit available to the retailer for utilizing more than one strategy. In this scenario, the cost benefits are almost negligible. Even for a retailer the size of Walmart, adding a second strategy reduces the total supply chain cost by approximately 0.1%, and adding a third reduces costs only 0.05% more. Even for the "super-Walmart", the reduction for adding a second strategy is approximately 0.15%, and adding the third strategy again reduces the costs only about 0.05% more.

Note that this is the relative cost reduction from the total supply chain cost. However, for any given retailer volume, there is a lower bound of supply chain cost that must be paid by the retailer. We can find this lower bound by assuming zero demand variance and zero lead time variance. Under these assumptions, no additional safety stock needs to be held. As such, the supply chain cost is generated solely by the transportation cost and pipeline inventory cost. Under this new objective function, we can re-optimize to find the lower bound of the total supply chain cost.

Under these cost parameters, this lower bound of supply chain cost is approximately 90% of the optimal total supply chain cost with variance included. As no supply chain strategy can ever reduce costs below this lower bound, we can feasibly reduce the total supply chain cost by no more than 10%. This 10% is the "potentially reducible" cost, and if we instead compare the cost reduction generated by the optimal multi-strategy to this "potentially reducible" cost, the relative value increases by a factor of ten. As such, for these parameters, we can say that the relative cost reduction can approach 2% at high volumes. This factor of ten increase applies to this and all subsequent relative cost reduction figures in this section.
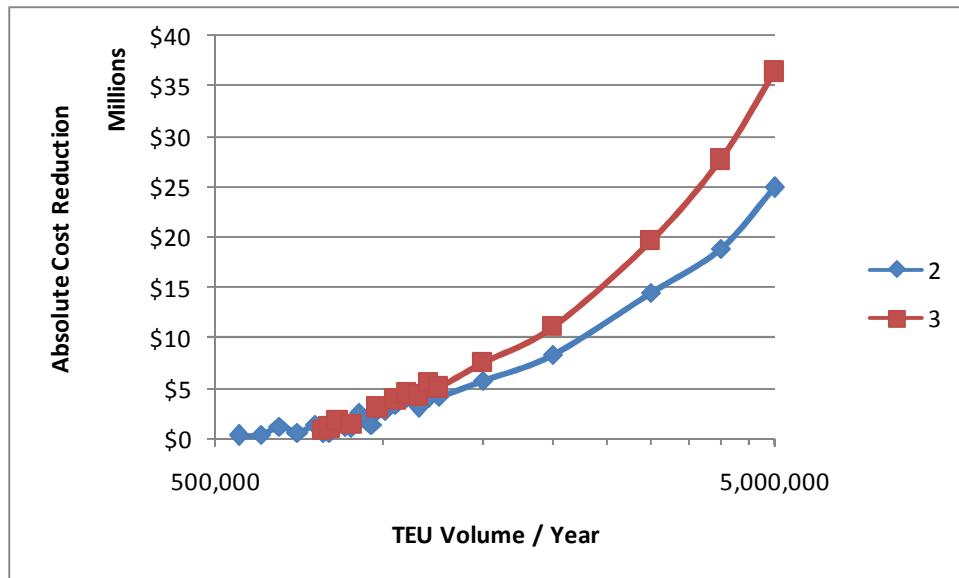
Figure 7-10. Absolute Cost Reduction for an Average US Retailer By Utilizing Multiple Strategies, All Goods Included
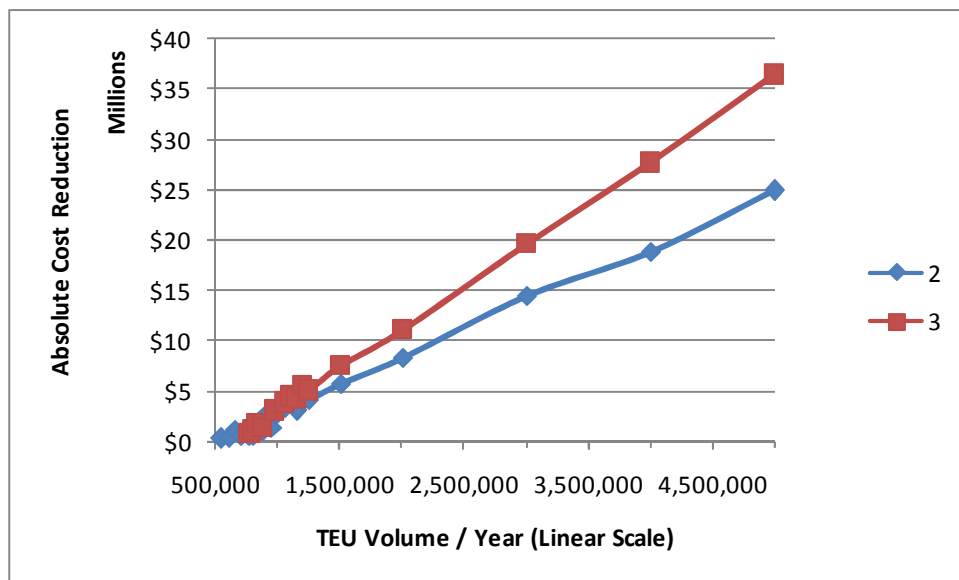

Figure 7-11. Absolute Cost Reduction for an Average US Retailer By Utilizing Multiple Strategies, All Goods Included – Linear Scaled Volume Axis

If we examine this in absolute dollars, we see that under these transportation cost and transit time parameters, a Walmart sized retailer will reduce their total costs by no more than $5 million per year, even with access to three strategies. Even the "super-Walmart" sees a reduction of only $25 million for two strategies and approximately $35 million for three strategies. As the volume of the retailer increases, the cost reduction increases approximately linearly. This becomes clear when we examine the chart with the volume axis scaled linearly.

We will now show the same analysis for the truncated goods valuation distribution. That is, the analysis discusses how to split strategies and the cost reductions available by utilizing multiple strategies, given that we are ignoring all goods valued at $40 per cubic foot or greater.
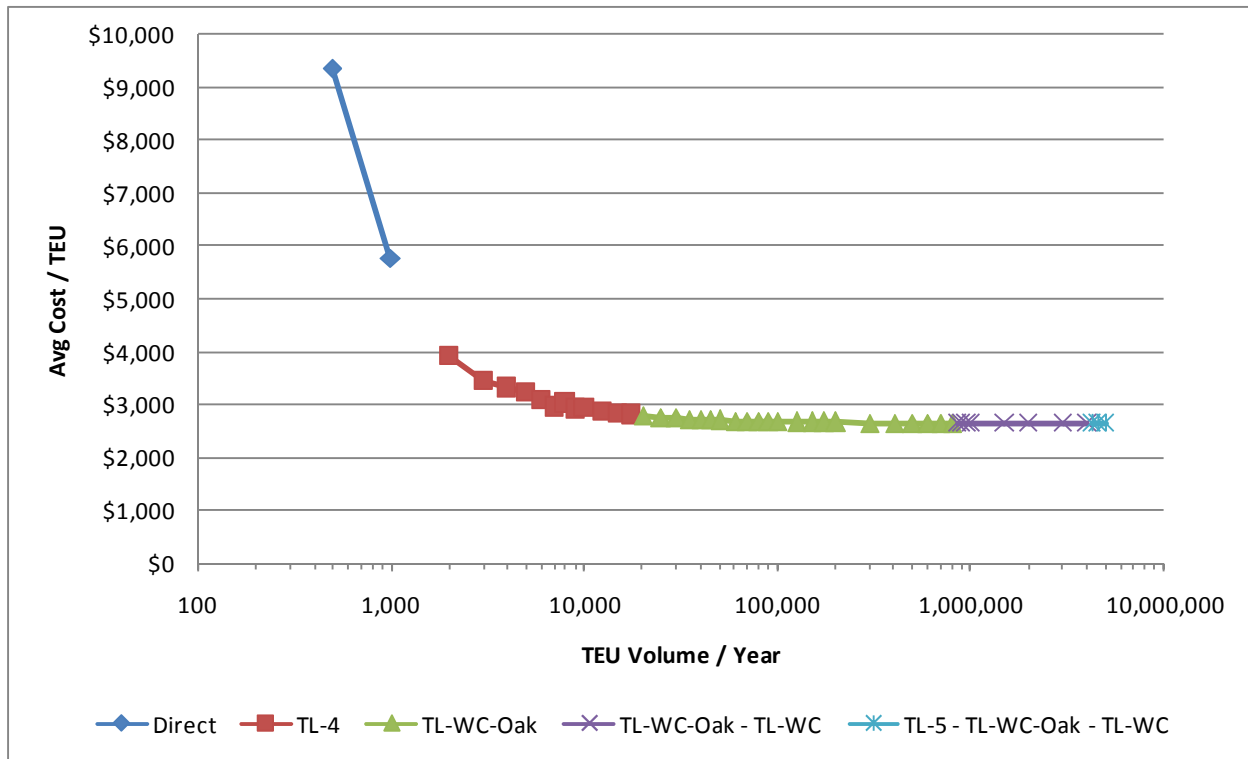
Figure 7-12. Average Cost Per TEU and Optimal Strategy for an Average US Retailer with the Capability to Handle Multiple Strategies, Goods Limited to Valuations Under $40

We see a similar pattern here, with a few differences. As we are examining a set of goods with a different mean valuation, we see that the dominant single strategy at the higher volumes (TL-WC-Oak) uses more ports than the dominant single strategy in the full distribution (TL-WC). Additionally, because the most expensive goods in this distribution are only $30 per cubic foot, the model will never recommend that a set of goods use the TL-LA strategy. As such, it does not suggest a multiple strategy solution until an importing volume of over 850,000 TEUs per year. It doesn't recommend splitting into a third strategy until approximately 4,250,000 TEUs per year, which is substantially larger than the current largest US importer. The similarity of these strategies, all multi-port Trans-loading strategies, suggests that the minor benefits from utilizing different but similar strategies for different valuations of goods is outweighed by the cost of the increased partial container round-up factor caused by splitting goods up into different supply chains.

As this valuation distribution includes less expensive goods, we would expect that the average cost per TEU would be lower than the full distribution. This is borne out by the data. The 1,000 TEU per year retailer has a cost of about $5,750 per TEU. This drops to below $4,000 at only 2,000 TEUs, below $3,000 at 7,000 TEUs, and converges to approximately $2,650 at high volumes.
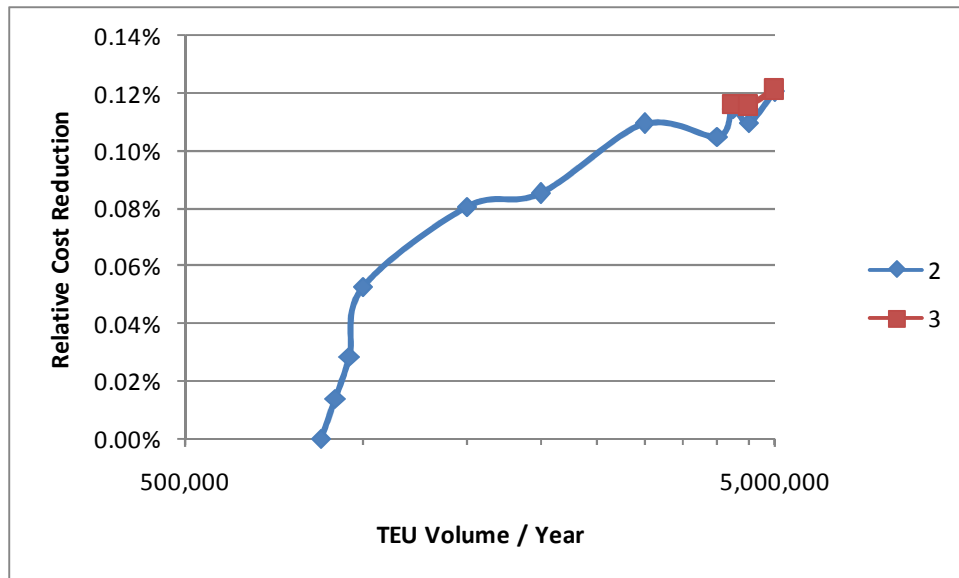
41

Figure 7-13. Relative Cost Reduction for an Average US Retailer By Utilizing Multiple Strategies, Goods Limited to Valuations Under $40
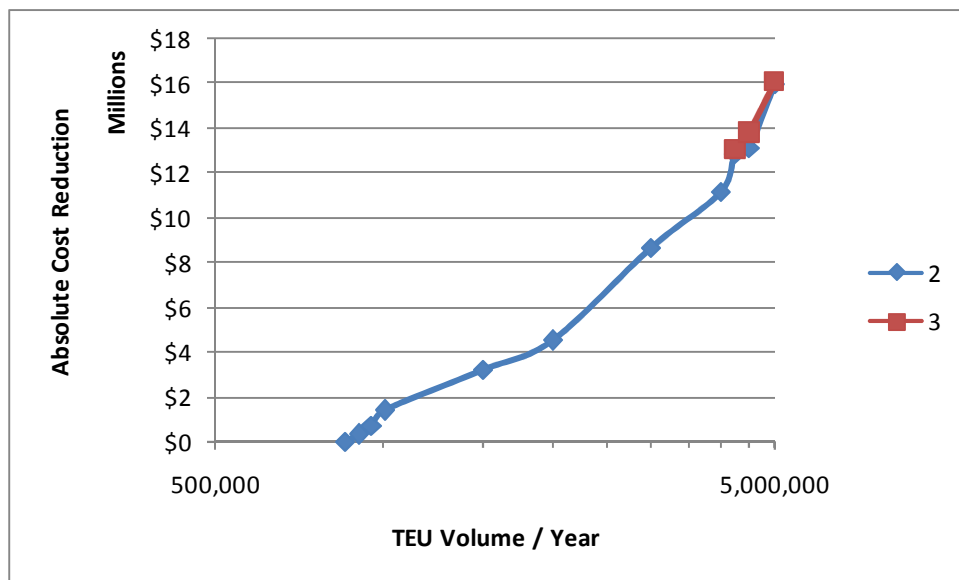

Figure 7-14. Absolute Cost Reduction for an Average US Retailer By Utilizing Multiple Strategies, Goods Limited to Valuations Under $40

Due to the limited diversity of goods in the supply chain, the cost reductions for the truncated value distribution diminish even further. The Walmart sized retailer sees a relative cost reduction of approximately 0.05%, under $2 million per year. The "super-Walmart" retailer sees a maximum benefit of 0.12%, about $16 million per year. Adding a third strategy is only viable for the very largest retailers and the benefits over two strategies is minimal. Because this truncated value distribution does not include the most expensive goods, there is no need for the TL-LA strategy to be used. The multi-port trans-loading strategies generate such similar total supply chain costs that adding additional strategies provides negligible benefit.

Thus, we must conclude that for this parameter set, it may not be worthwhile for a retailer to take advantage of a multi-strategy supply chain. It is likely that there will be operational overhead and indirect costs such as to negate any supply chain cost reduction generated by a multi-strategy solution.

7.2.2. *Multi-Strategy – Top-5 Retailer*

We will now examine multiple strategy recommendations for the transportation rates, transit times, and RDC distribution parameters from case study top-5 US retailer.
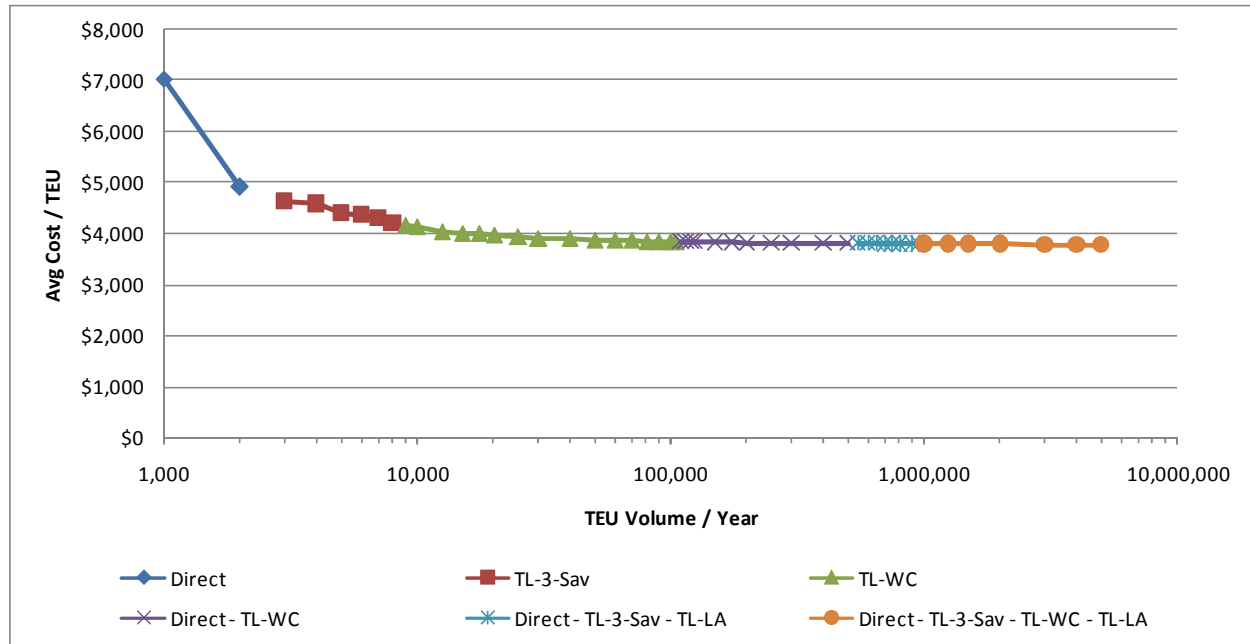

Figure 7-15. Average Cost Per TEU and Optimal Strategy for the Case Study Top-5 US Retailer with the Capability to Handle Multiple Strategies, All Goods Included

Again, we note that until we start splitting into multiple strategies, the single strategy matches with the recommended strategy in the single strategy section for this scenario. However, as this retailer has favorable Direct shipping rates, we see that the analysis recommends splitting into multiple strategies at much smaller volumes, at only 110,000 TEUs per year. The analysis now recommends that the first split be into a Direct shipping portion and a Trans-loading portion, the latter portion using LA-LB and Seattle. Above 500,000 TEUs, the analysis recommends splitting into three strategies: the cheapest goods shipped Direct; the medium value goods Trans-loaded at LA-LB, Seattle, and Savannah; and the most expensive goods Trans-loaded at LA-LB only. Above 1,000,000 TEUs, we add back in a fourth strategy, Trans-loading at LA-LB and Seattle. We see that under these parameters, the specificity of which ports to Trans-load through has enough of a cost benefit to outweigh the additional cost of the partial container round-up factor. Additionally, we now see a Direct strategy being used for the less expensive goods, and that the two-strategy solution splits goods into those that should use a Direct strategy and those that should use a multi-port Trans-loading strategy.

The cost per TEU is slightly higher under these parameters than that for the average retailer. At the smallest volume, the average cost per TEU is just over $7,000. It doesn't drop below

$4,000 until 20,000 TEUs, and converges to approximately $3,780. This is likely due to the fact that the transportation rate data was captured at an earlier time for the average retailer than for the case study retailer.
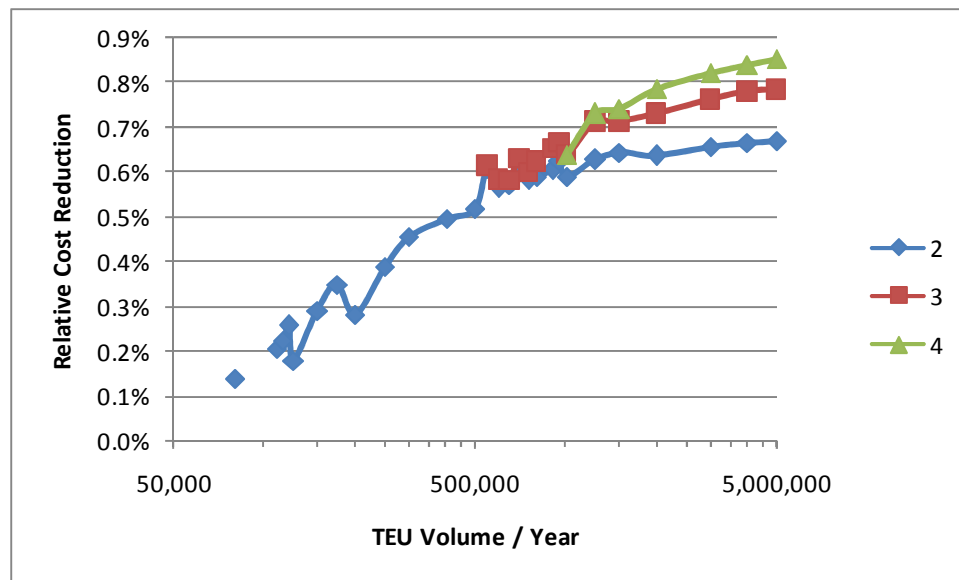

Figure 7-16. Relative Cost Reduction for the Case Study Top-5 US Retailer By Utilizing Multiple Strategies, All Goods Included
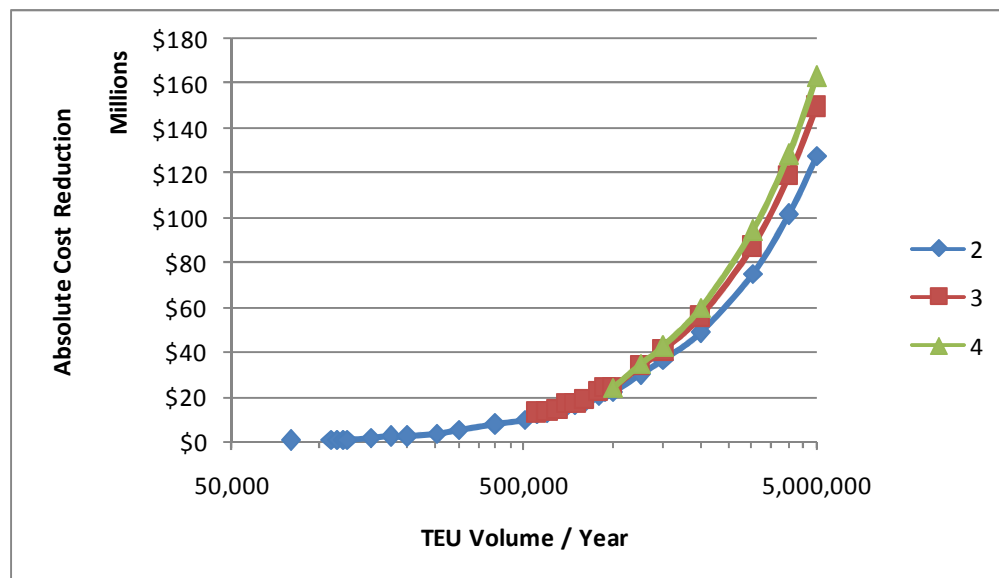

Figure 7-17. Absolute Cost Reduction for the Case Study Top-5 US Retailer By Utilizing Multiple Strategies, All Goods Included

Under these transportation rate and lead time parameters, we now see a much greater cost reduction for the multi-strategy solution, as well as a real cost reduction for much smaller retailers. A retailer importing about 100,000 TEUs per year (approximately the size of GE or Costco) utilizing a two-strategy supply chain would see a benefit of about 0.2% over the single optimal strategy, which would be approximately $1 million per year. A Walmart sized retailer

would see a cost reduction of 0.6% for a two-strategy solution, with an additional 0.05% for a three-strategy solution, equivalent to $22 million for the two-strategy solution and an additional $2 million for the third strategy. For the "super-Walmart" retailer, we see a maximum cost reduction of about 0.65% for two strategies, about $130 million per year. Adding a third strategy reduces costs by an additional 0.1%, about $20 million more per year. The fourth strategy reduces costs further by about 0.07%, or $15 million per year. Thus, we see that if a retailer has access to favorable Direct shipping rates, taking advantage of a multi-strategy solution becomes much more profitable.

When considering the truncated distribution for goods values, the results exhibit a pattern similar to that for the complete distribution.
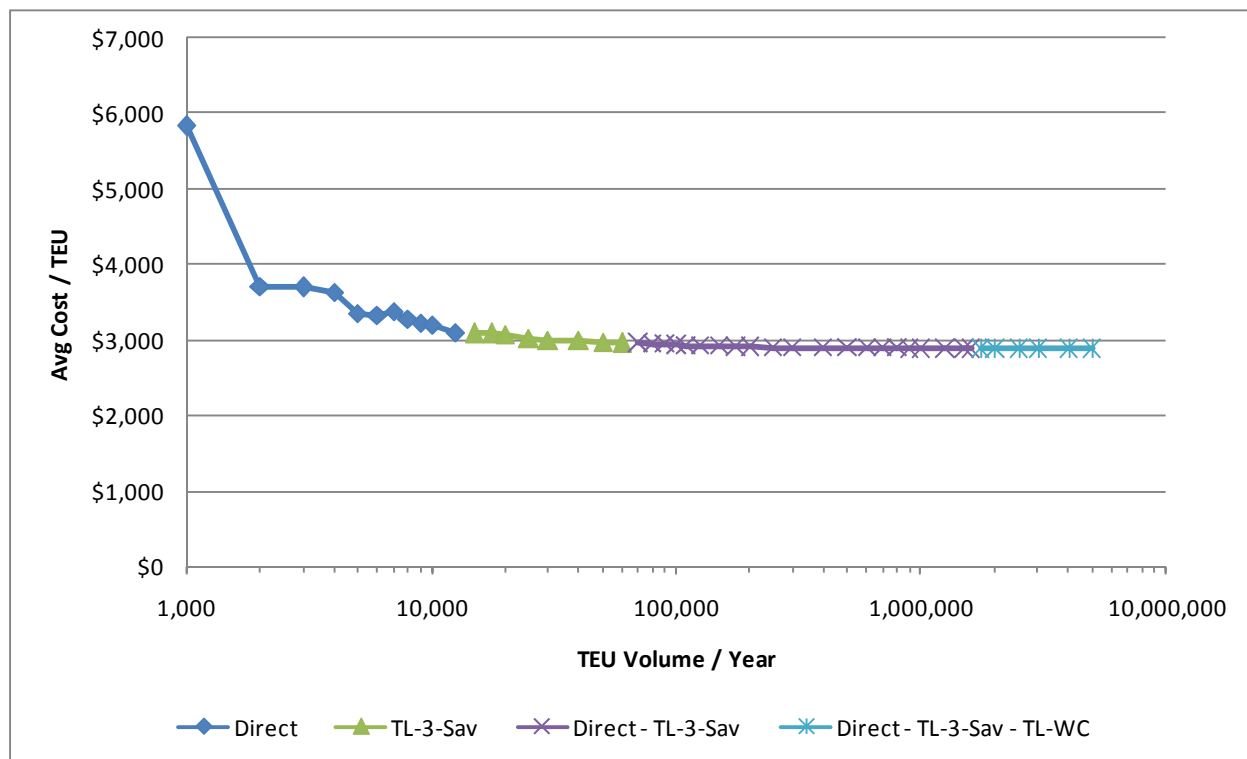

Figure 7-18. Average Cost Per TEU and Optimal Strategy for the Case Study Top-5 US Retailer with the Capability to Handle Multiple Strategies, Goods Limited to Valuations Under $40

The first split into a Direct-shipped portion and a Trans-loaded portion using three ports occurs at a volume of 70,000 TEUs per year. As we no longer have the expensive goods that necessitate the use of the Trans-load at LA-LB strategy, we don't recommend another split until a volume of 1,750,000 TEUs. This would split goods into those Trans-loaded at LA-LB and Seattle and those Trans-loaded at LA-LB, Seattle, and Savannah. As these strategies are so similar, we need a very large volume to justify such a split.

The cost per TEU is as we expect given the previous observations. It shows a lower level than when using the full value distribution for the case study retailer, but has a higher cost than that for the truncated distribution for the average US retailer. (Again, the latter effect has to do with the increases in transportation rates between the times data sets were prepared for the

average US retailer and for the case study retailer.) It drops below $3,000 per TEU at 40,000 TEUs per year and converges to approximately $2,880 at high volumes.
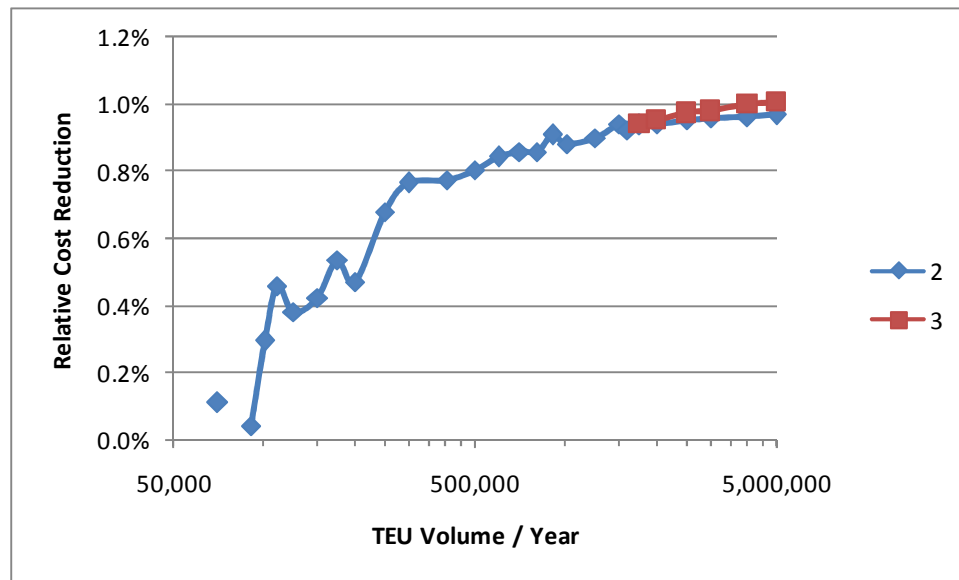

Figure 7-19. Relative Cost Reduction for the Case Study Top-5 US Retailer By Utilizing Multiple Strategies, Goods Limited to Valuations Under $40
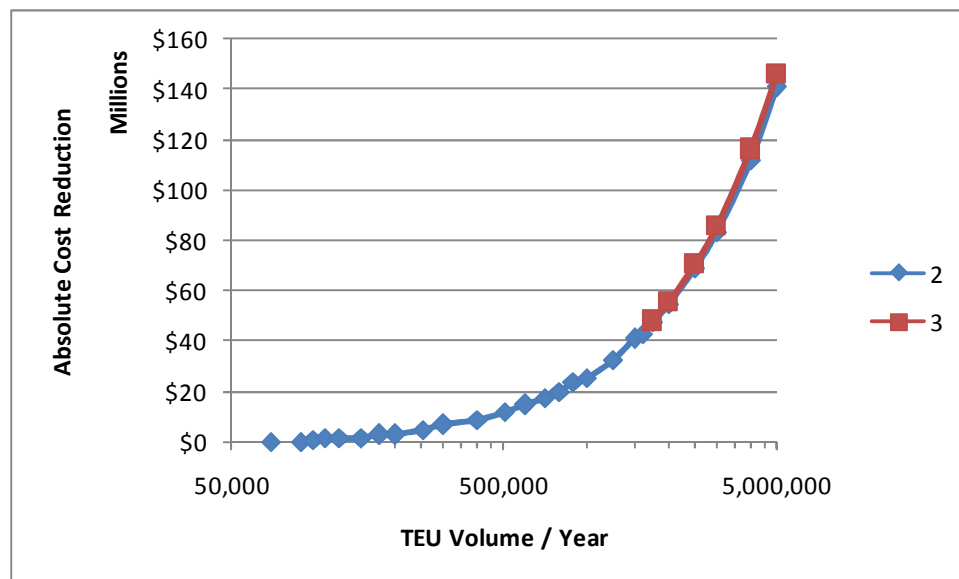

Figure 7-20. Absolute Cost Reduction for the Case Study Top-5 US Retailer By Utilizing Handle Multiple Strategies, Goods Limited to Valuations Under $40

Under these transportation rate and lead time parameters, we still see a larger relative and absolute supply chain cost reduction by allowing multiple importing strategies. The majority of this cost reduction comes from the split to a two-strategy solution, where we send the low-value items via a Direct strategy and the more expensive items via a Trans-loading strategy. The relative reduction is even greater than that for the complete goods value distribution. This is because the proportion of goods utilizing that second strategy is greater. The absolute cost reduction is only slightly greater than that for the complete value distribution. As the goods

being imported have a reduced average inventory holding cost, the total supply chain cost for these retailers will start out lower, and thus the increased relative benefit will be mitigated. For the 100,000 TEU retailer, there is a 0.3% cost reduction, again just under $1 million per year. The Walmart sized retailer will see a 0.9% reduction, approximately $25 million per year. The "super-Walmart" retailer will have approximately a 1% reduction, or $140 million per year. As we saw previously with the truncated goods value distribution, adding more than two strategies does not change the cost substantially. This is due to the fact that no goods will be recommended to utilize the TL-LA strategy, and the difference in costs between the multi-port Trans-loading strategies is minimal.

7.2.3. Multi-Strategy – Top-5 Retailer, Average US Retailer RDC Demand Distribution

Lastly, we will examine multiple strategy recommendations for the transportation rates and transit times from the case study top-5 US retailer and RDC distribution parameters from the average US retailer.
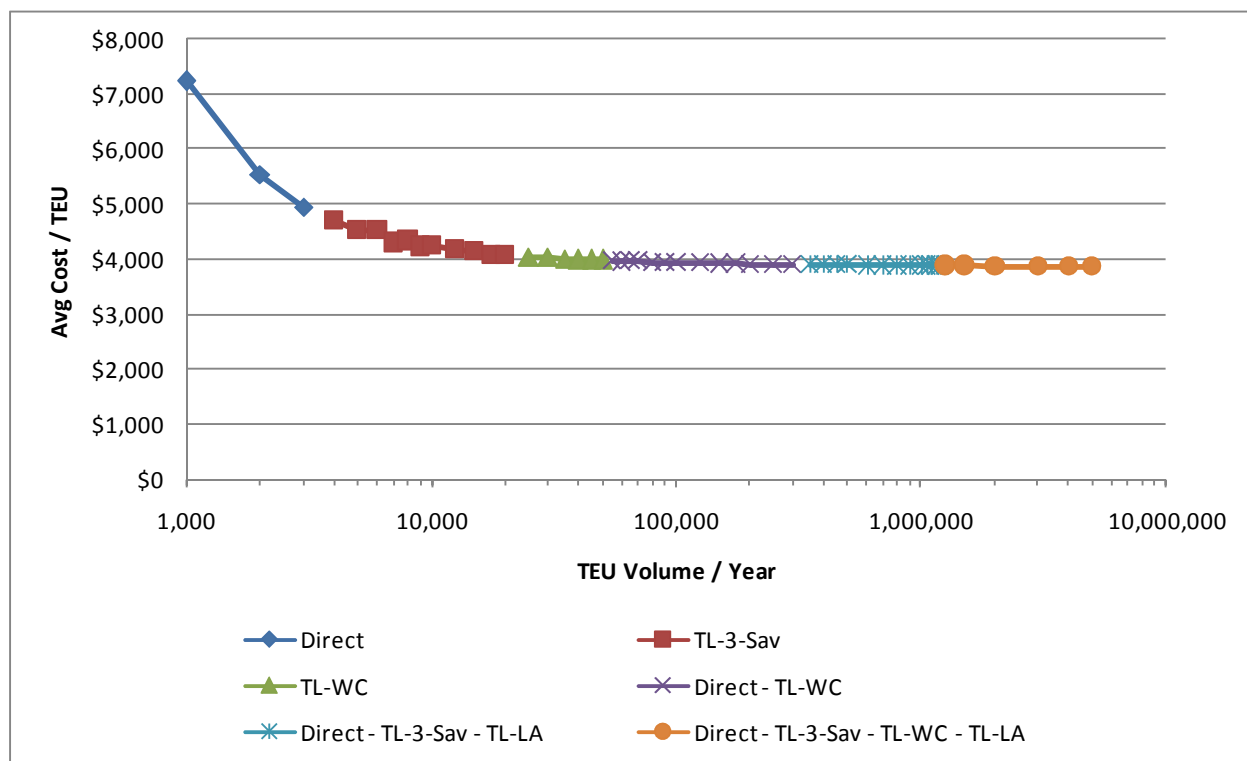

Figure 7-21. Average Cost Per TEU and Optimal Strategy for the Case Study Top-5 US Retailer with the Capability to Handle Multiple Strategies Using Average Retailer RDC Demand, All Goods Included

This shows a very similar pattern to that for the case study retailer using its own RDC demand distribution, but with two main differences. The recommendations for both the split from one to two strategies and the split from two to three strategies come at lower importing volumes. While in the previous scenario the split to two strategies comes at 110,000 TEUs per year, the version using average US retailer RDC demands starts using two strategies at 55,000 TEUs. The split from two to three strategies is similarly reduced from 550,000 TEUs per year to 350,000 TEUs. This suggests that for retailers that have built their national infrastructure to conform more to the average US retailer and have access to favorable Direct shipping rates, there

47

is more of an opportunity to benefit from multiple supply chain strategies, even at lower importing volumes.

The average cost per TEU remains very similar to that of the case study retailer. At the smallest volume, the average cost per TEU is now just above $7,200. It is just above $4,000 at 20,000 TEUs, and converges to approximately $3,870 at high volumes. Costs are slightly higher here than in the case study retailer scenario. This is likely due to the transportation rates reflecting the infrastructure purely of the case study retailer. Additional demand in regions that this retailer is not built to handle will slightly increase costs.
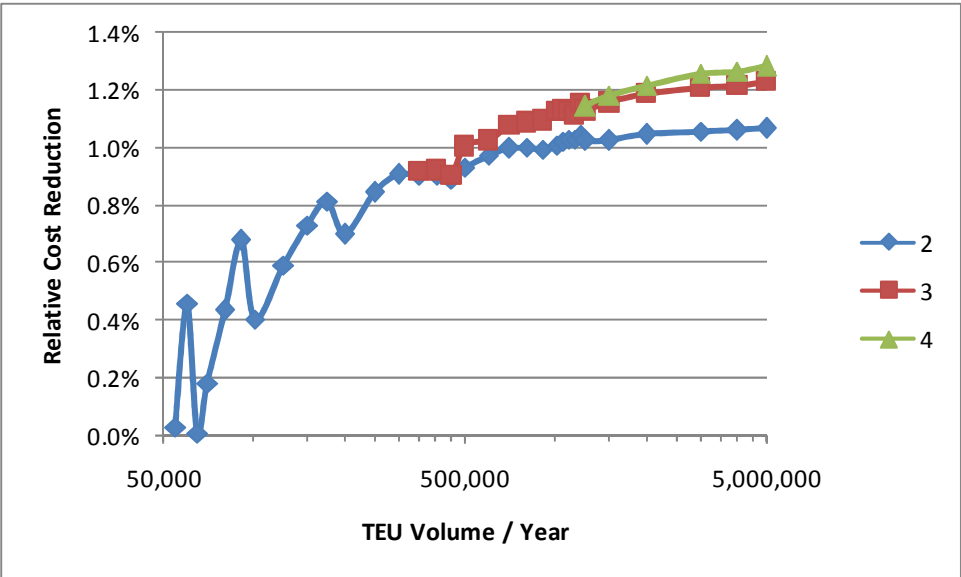

Figure 7-22. Relative Cost Reduction for the Case Study Top-5 US Retailer Using Average Retailer RDC Demand By Utilizing Multiple Strategies, All Goods Included

Figure 7-23. Absolute Cost Reduction for the Case Study Top-5 US Retailer Using Average Retailer RDC Demand By Utilizing Multiple Strategies, All Goods Included

Again, we see a similar pattern to what we saw for the case study retailer's demand distribution, with an increased benefit coming at lower volumes. Now for the 100,000 TEU retailer, there is a benefit of 0.6%, under $2 million per year of absolute cost savings. The Walmart sized retailer utilizing two strategies will have a cost reduction of 1%, about $40 million per year. Adding a third strategy, sending some goods via the TL-LA strategy will further decrease the costs by 0.12%, or $5 million per year. For the "super-Walmart" retailer, the relative cost reduction only slightly increases to 1.07%, approximately $210 million per year. The third strategy allowed further reduces costs by 0.16%, about $30 million per year. Adding the fourth strategy reduces costs by only an additional 0.05%, under $10 million per year.

Considering the truncated goods valuation distribution for this case shows an interesting but not unexpected feature.
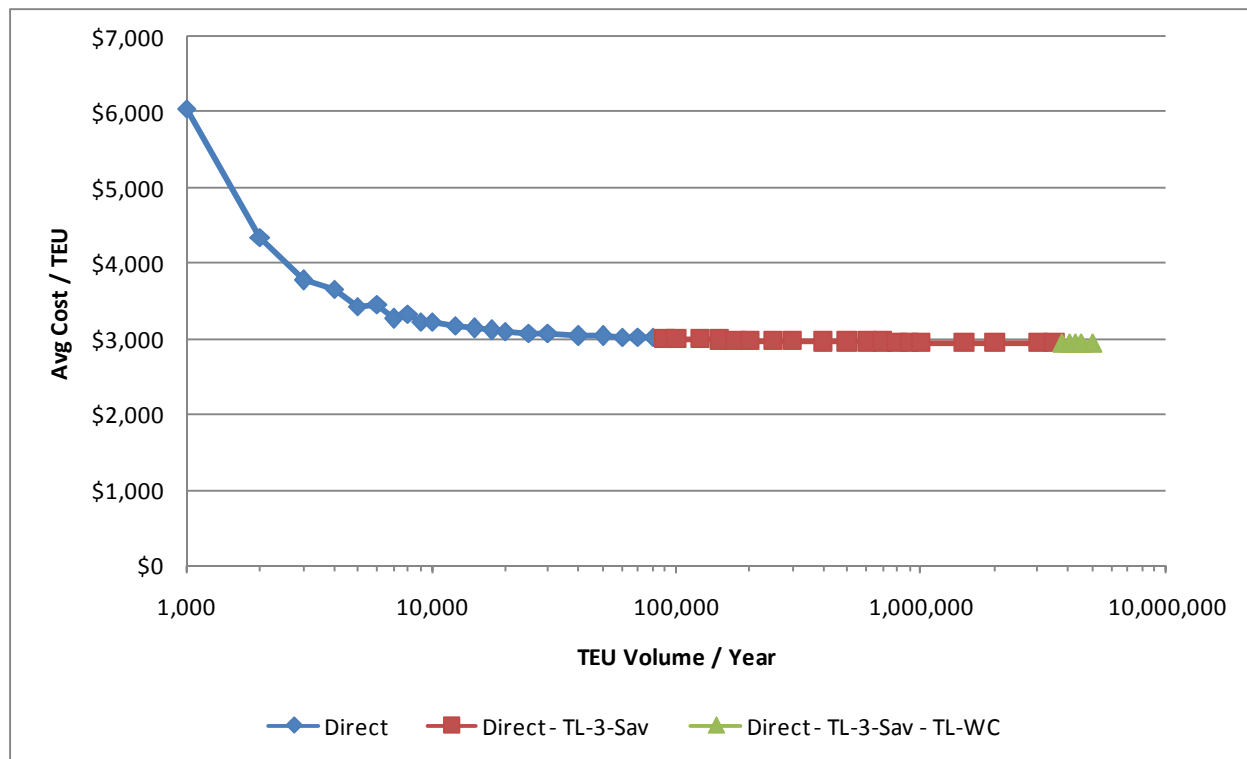
Figure 7-24. Average Cost Per TEU and Optimal Strategy for the Case Study Top-5 US Retailer with the Capability to Handle Multiple Strategies Using Average Retailer RDC Demand, Goods Limited to Valuations Under $40

We no longer see single strategy recommendations for Trans-loading. This is not surprising, as the single optimal strategy remained Direct shipping, even at the highest volumes for the case study rates with the average US RDC demand scenario at $15 per cubic foot average goods valuation. The split to two strategies happens at 90,000 TEUs per year. The split to three strategies occurs at a volume of 3,750,000 TEUs.

The cost per TEU is as we expect given the previous observations. It shows a lower cost than the full distribution for the case study retailer, but a higher cost than the truncated distribution for the average US retailer. The cost is just above $3,000 per TEU at 40,000 TEUs per year and converges to approximately $2,950 at high volumes.

49
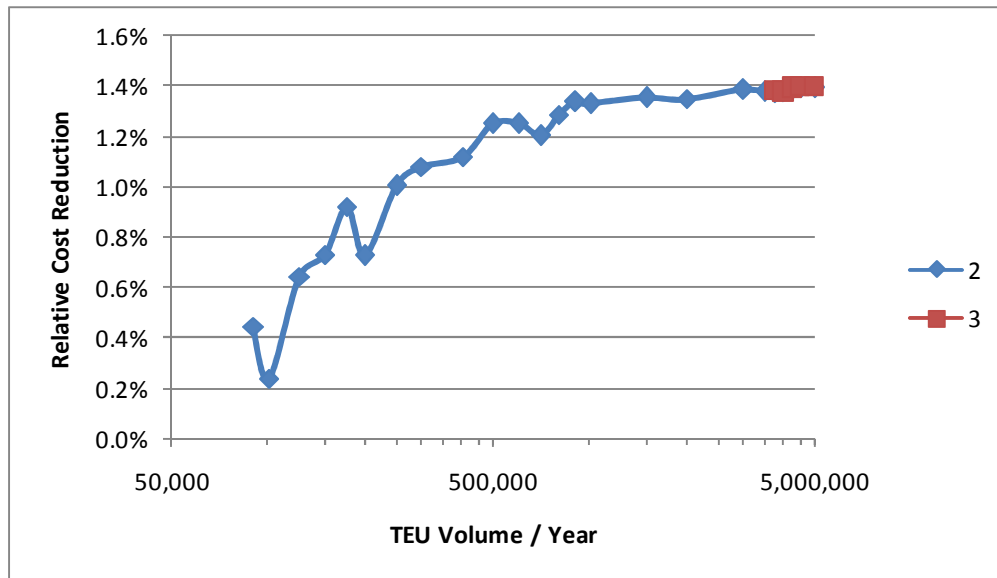
Figure 7-25. Relative Cost Reduction for the Case Study Top-5 US Retailer Using Average Retailer RDC Demand By Utilizing Multiple Strategies, Goods Limited to Valuations Under $40
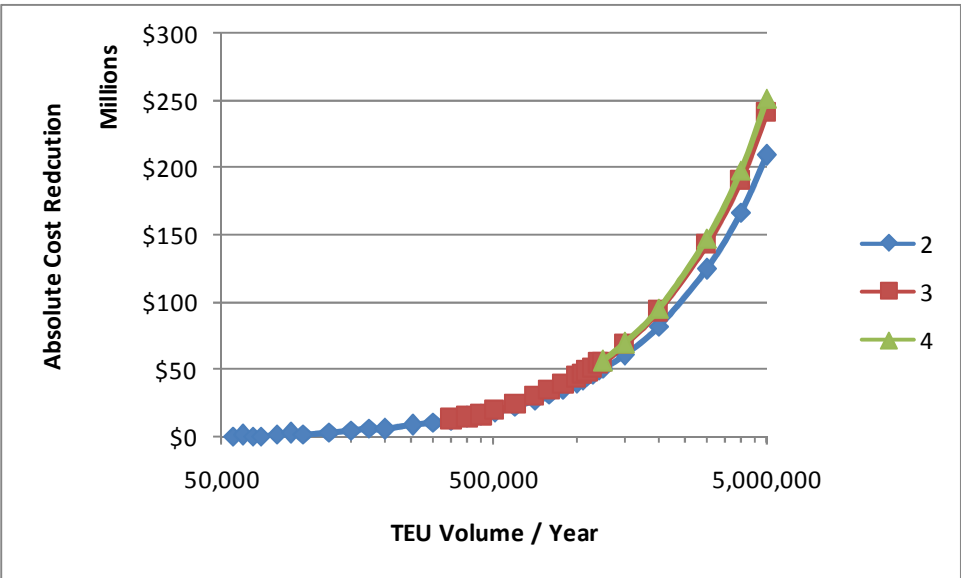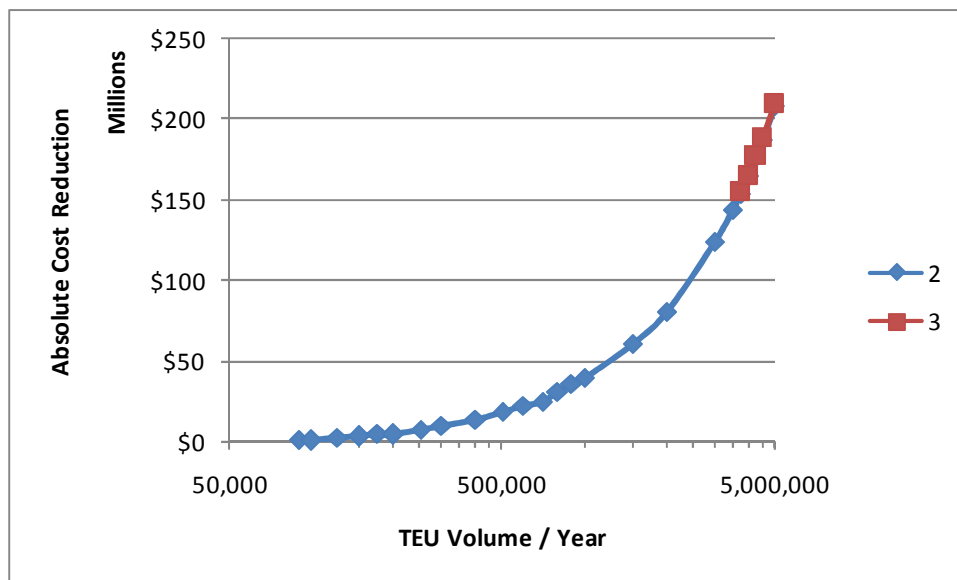

Figure 7-26. Absolute Cost Reduction for the Case Study Top-5 US Retailer Using Average Retailer RDC Demand By Utilizing Multiple Strategies, Goods Limited to Valuations Under $40

We see similar patterns here as previous. Splitting the retailer such that the inexpensive goods are imported via a Direct strategy while the expensive goods are imported via Trans-loading shows the bulk of the benefit. Again, when the third strategy utilized is not a single port trans-loading strategy, additional benefit from that third strategy is negligible. For the 100,000 TEU per year retailer, the relative benefit is approximately 0.65%, or just under $2 million per year. The Walmart sized retailer shows a cost reduction of just over 1.3%, approximately $40 million per year. The "super-Walmart" retailer has a cost reduction of 1.4%, or $210 million per year. The third strategy again adds very little when using this truncated good valuation distribution, under 0.01% cost reduction, about $1 million per year.

Using this model, for a given set of transportation rates, RDC demands, and a goods valuation distribution, we can pinpoint the annual volumes that would benefit from a multiple strategy solution, what sets of goods should be shipped via which strategies, and which RDCs should be allocated to each port within each strategy.

While the conclusion is clearly dependant on the goods value distribution for these retailers as well as the particular cost structure negotiated with third-party logistics providers, we believe that there are at least 10, and possibly up to 40 US retailers that operate at a large enough importing volume to potentially take advantage of splitting their goods into multiple importing supply chain strategies. The more varied the goods imported by the retailer, the more likely that they can take advantage of this splitting. The bulk of this cost reduction will be generated by splitting goods into those that are imported via a Direct strategy and those that are imported via a Trans-loading strategy, as long as the cost structure is such that a retailer can take advantage of a Direct shipping strategy. Adding a third strategy may be able to generate value, but generally only when that new strategy is to import goods by Trans-loading at a single port, specifically in our case at LA-LB.

8. Port Redundancy Analysis

Interviews with a number of large retail importers reveal that in actuality these large retailers manage import warehouses and trans-loading operations at more ports than would be considered optimal by the analysis of the preceding sections. For example, for their normal operations, the case study retailer employs a modified 4-port trans-loading strategy, with import warehousing and trans-loading infrastructure at Los Angeles-Long Beach, Seattle, Savannah, and Norfolk. For any given product in its portfolio, they will generally import into three of the four ports listed above, always using LA-LB and Seattle, and for goods destined for the east coast entering through either Savannah or Norfolk. As per section 7.1.2., for a total import volume of approximately 350,000 TEUs per year and an average goods value of $25 per cubic foot, the single optimal strategy would use only two ports: LA-LB and Seattle. As per section 7.2.2., if we were to allow the case study retailer to use a multiple strategy solution, our analysis would suggest adding only Direct shipping operations, with no need for more trans-loading infrastructure than at the two aforementioned ports. At a slightly lower average goods value, the model does recommend the use of Savannah as a third port for trans-loading operations. We do not find any cases for the case study retailer where an optimal strategy would be to use all four ports.

Similar patterns are found for other retailers. Our model recommends either using fewer ports for trans-loading import operations, or using as many ports as are actually used only for a very small subset of goods. We must now consider why these retailers build and utilize this infrastructure for their importing operations, as the costs for warehousing rent and trans-loading operations at any given port are substantial.

There are two potential factors that we will touch on briefly, but will not analyze in depth. The first factor is capacity. A retailer may for some reason have only a certain amount of capacity for importing at a given port, perhaps in terms of warehouse space or in trans-loading labor or operating shifts available at facilities in the hinterland of that port. For a long-term steady state analysis of a retailer's operations, neither of these should be an issue. We assume

51

that warehouse space can be freely expanded as necessary with either sunk costs for building or additional rent payment. Similarly, trans-loading capacity is provided by third-party logistics companies, and can generally be expanded as necessary with new contracts.

The second factor that we will not analyze is that of negotiating leverage. By utilizing more ports for warehousing and trans-loading infrastructure, the retailer may be able to negotiate reduced costs for both that infrastructure as well as transportation costs. We have already noted in the previous section that the case study retailer has been able to secure comparatively lower rates for their direct shipping transportation than the averages of rate quotations to many importers. It is conceivable that by having infrastructure at additional ports, they can negotiate better rates for adding trans-loading volume at any given port by playing the landlords, third-party logistics companies, and transportation carriers at these different ports against each other. We cannot quantify how much of a cost reduction this will provide to any given retailer, as these negotiations will certainly be kept private.

Robustness or redundancy is another reason to build infrastructure at more ports than may be optimal according to a steady state model. There may be cases where a port becomes more costly to use for a short amount of time, due to some sort of shock. In 2004, the ports of Los Angeles and Long Beach were in a situation such that there were many more incoming container ships than they could handle during their peak season. They were over their capacity and as such their container dwell times sky-rocketed. We consider events such as a labor strike or the 2004 over-capacity meltdown in Los Angeles and Long Beach as examples of such a shock. If a shock were to occur at any given port, the cost of using that port would increase substantially. By having infrastructure and rates at other ports in place before such a shock, a retailer may attempt to avoid some of that additional cost.

We can attempt to model the additional cost to a retailer due to such a shock. We will model the cost increases to the total supply chain as increases to dwell time at the ports of Los Angeles and Long Beach until they become basically unusable. We have chosen LA-LB as our port to "shock" as it is clearly the most common port recommended for use in our model, and will thus show the largest total cost increases. As the transportation time through LA-LB increases, the inventory cost of imports allocated to that port will increase. Given different baseline strategies, we will examine how the total supply chain cost increases as we increase the dwell time through LA-LB, up to an additional 50 days. At 50 additional days through LA-LB, no retailer tested will allocate any imports to LA-LB unless forced to.

8.1. Locked Strategies

As in the previous section, we will run this analysis for all combinations of importing volume and declared goods values. We will use the single strategy with average US retailer costs as a baseline (parameters as per Section 7.1.1.). We will first examine the case where each retailer must use the same set of ports available to them in that baseline. For example, for a retailer with an importing volume of 10,000 TEUs per year and a declared goods value of $50 per cubic foot, the optimal single strategy is TL-WC, or trans-loading at LA-LB and Seattle. For this section of the analysis, we will allow the use of both LA-LB and Seattle. We will also allow imports destined for an RDC that had previously been allocated to LA-LB to shift to Seattle as the cost through LA-LB increases. We have selected six representative retail importing volumes to focus this analysis: 1,000 TEUs per year; 3,000; 7,000; 10,000; 70,000; and 400,000. These six

representative volumes provide enough variation to examine all possible strategies for the baseline LA-LB transit time.

Figure 8-1. Cost Increase Due to Disruption for Sample Retailers with $5 Good Valuation, Required to Use the Same Strategy as would be Optimal Under No Delay

At a declared goods value of $5 per cubic foot, we see two different strategies represented: Direct Shipping for the lowest volumes, and trans-loading through five ports for the higher volumes. The increase in cost for the Direct shipping strategies stays pretty low, approximately 1% at the most, even when LA-LB becomes unusable. Because of the distributed nature of this strategy, the retailers can mostly avoid LA-LB while not increasing their costs too much. For those retailers whose baseline optimal strategy is TL-5, we see their total costs increasing between 1% and 2% for an additional dwell time below 10 days, up to approximately 4.5% additional cost when LA-LB becomes unusable.
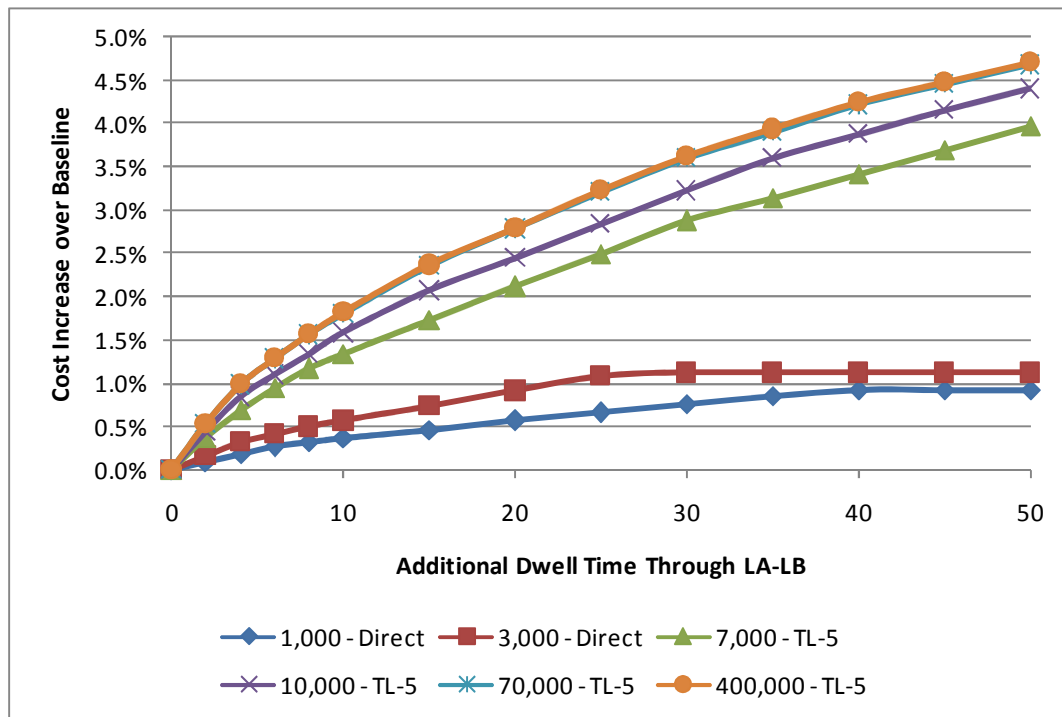
Figure 8-2. Cost Increase Due to Disruption for Sample Retailers with $10 Good Valuation, Required to Use the Same Strategy as would be Optimal Under No Delay

For the $10 per cubic foot goods value retailers, we see a larger cost increase, as expected. The increase in dwell time affects the inventory cost, which grows with the declared value. The retailer using the Direct strategy as baseline still sees an increase of approximately 1%. The TL-5 retailers now see an increase of between 2% and 3% at an additional dwell time of 10 days, with a maximum increase of between 5% and 6%. The other retailers all have different optimal baseline strategies, utilizing fewer and fewer ports as the volume increases. The additional cost increases faster and has a larger maximum with fewer available ports. At 10 days, the retailers whose baseline strategies utilize between two and four ports see a cost increase of between 3% and 4% at 10 days of additional dwell time, and about 7% at maximum. Clearly, as we reduce the number of ports available to a retailer, the more cost will be incurred by a shock to any one of those ports.

Figure 8-3. Cost Increase Due to Disruption for Sample Retailers with $20 Good Valuation, Required to Use the Same Strategy as would be Optimal Under No Delay

As the declared goods value increases, the cost increase reaches its maximum at fewer and fewer days of additional dwell time. Due to higher inventory cost through LA-LB, more of the RDCs allocated to LA-LB in the baseline strategy will shift to a different available port. While the maximum cost increase stays approximately the same for a given baseline strategy, we see the increase at the additional 10-day dwell time grows to between 5% and 6% for the retailers using two to four port baseline strategies for a goods value of $20 per cubic foot.
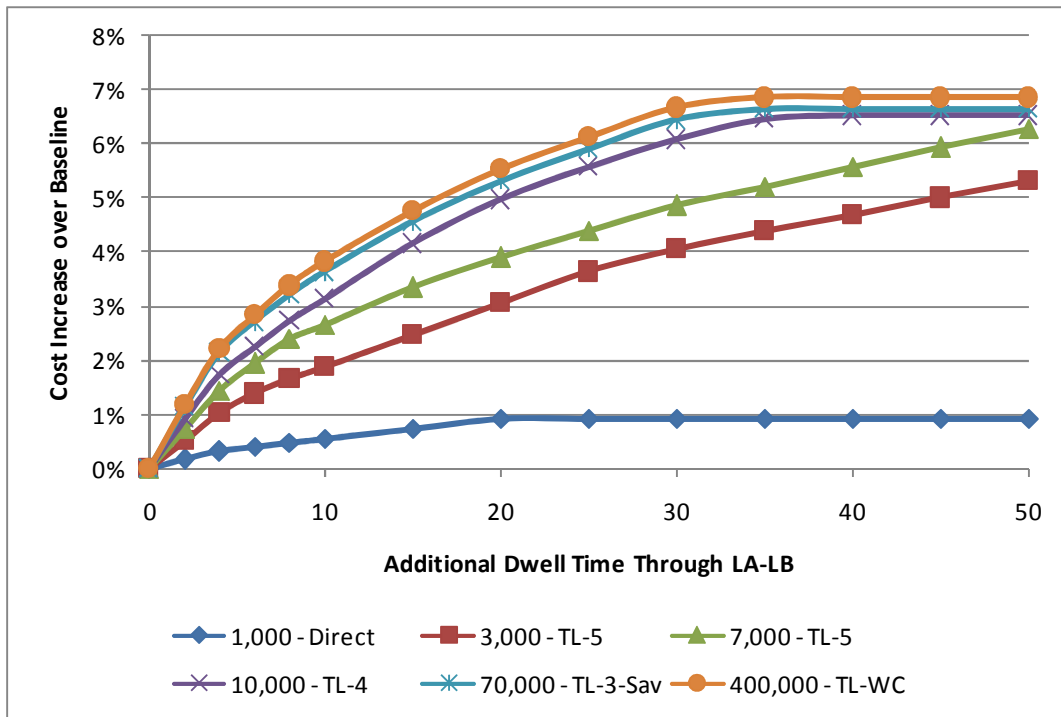
Figure 8-4. Cost Increase Due to Disruption for Sample Retailers with $30 Good Valuation, Required to Use the Same Strategy as would be Optimal Under No Delay

At $30 per cubic foot declared goods value, we see most RDCs shifting away from LA-LB at 10 days of additional dwell time. The maximum additional cost remains between 6% and 7% for these retailers, all using between two and four ports in their baseline optimal strategies.
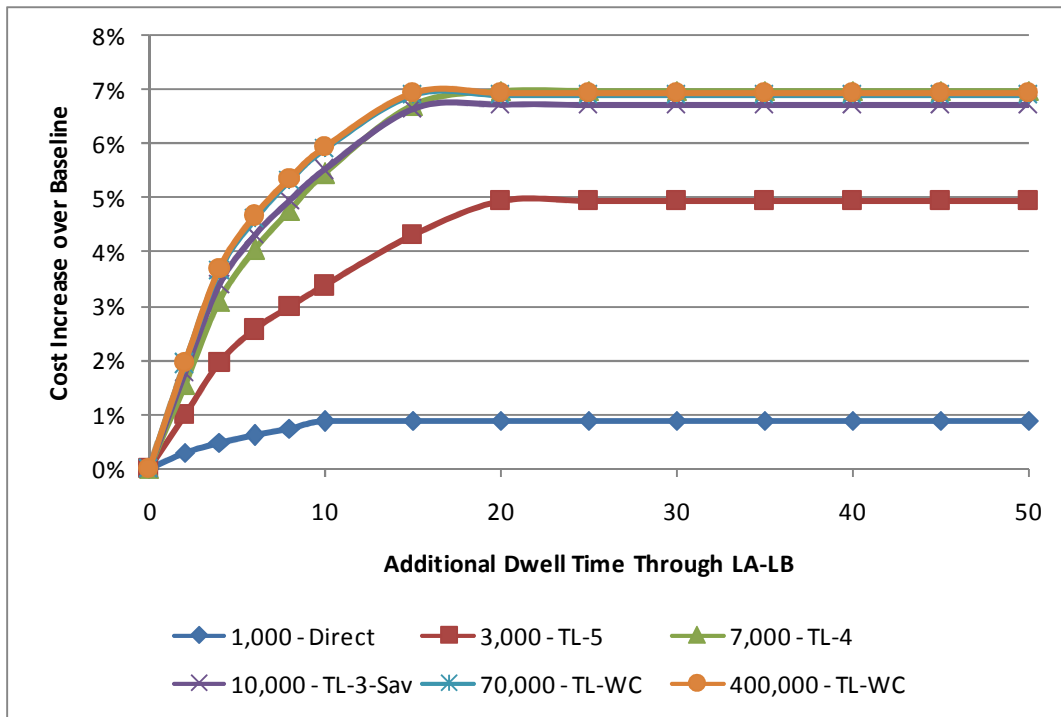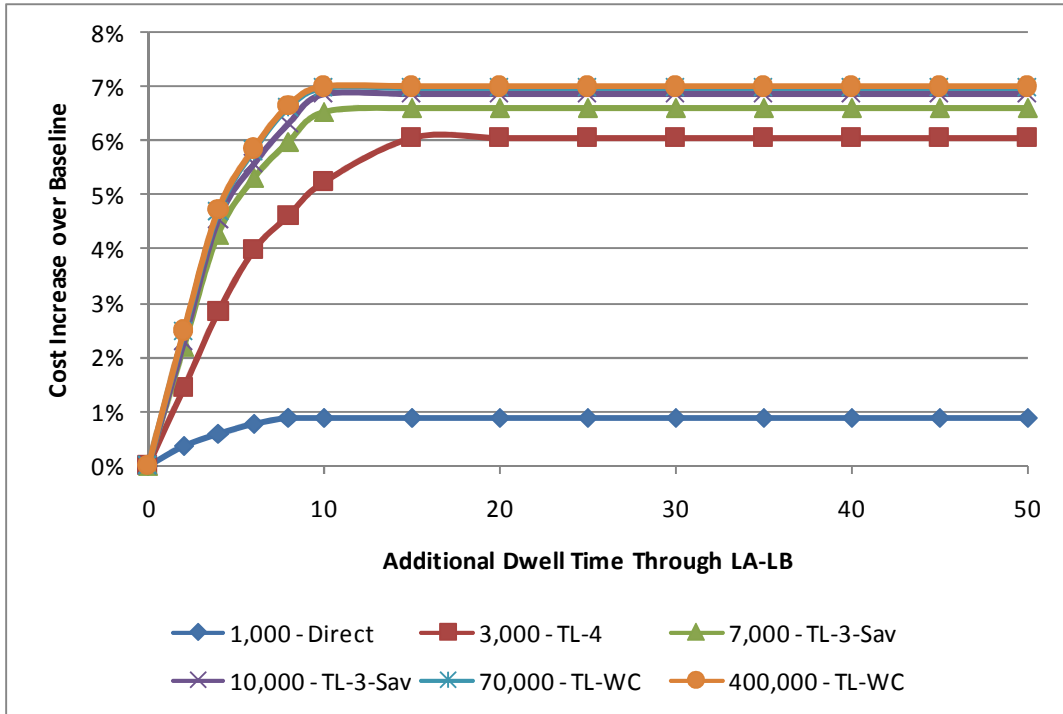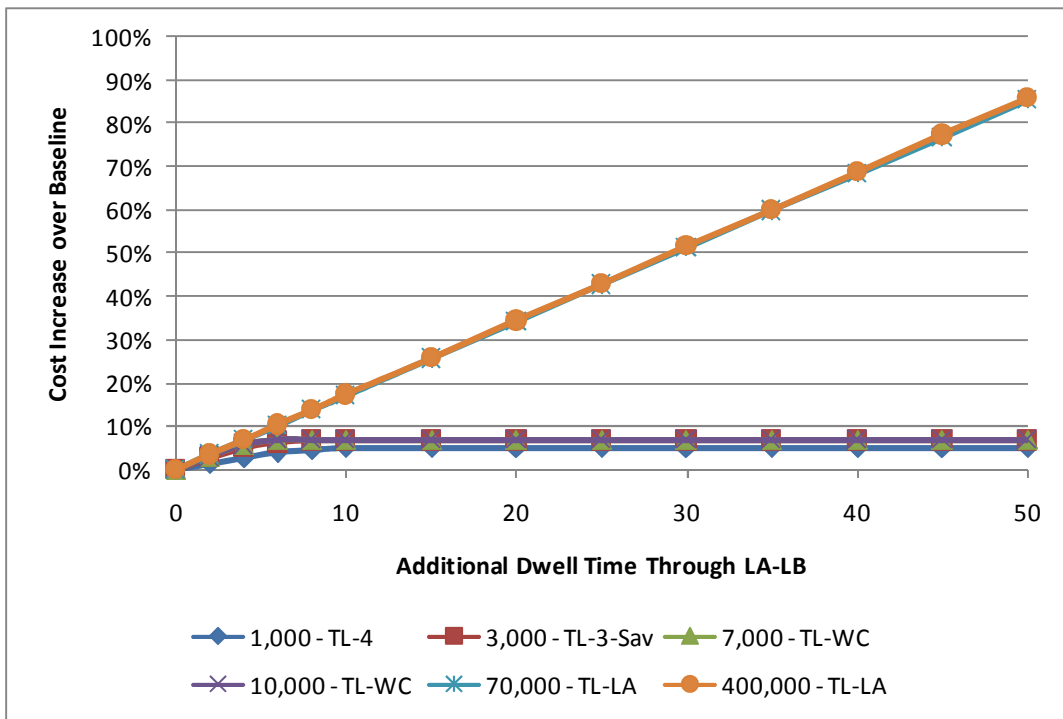

Figure 8-5. Cost Increase Due to Disruption for Sample Retailers with $50 Good Valuation, Required to Use the Same Strategy as would be Optimal Under No Delay

At a declared goods value of $50 per cubic foot, we now introduce retailers whose optimal baseline strategy is to trans-load at LA-LB only. If these retailers are locked into only using LA-LB, their costs will increase linearly with the additional dwell time. For those retailers with a TL-LA baseline, at 10 days of additional dwell time, we see an increase of approximately 17%. With the 50 day disruption, these retailers would almost double their total supply chain cost. Obviously, a shock to a retailer's only available port could cause disastrous cost increases.

Even if that shock does not last a long, it could affect the retailer's total yearly supply chain cost. We can formulate a simple example of a TL-LA retailer encountering a single event that causes LA-LB to be unavailable for exactly 10 days, but regaining full capacity and clearing all backed up goods immediately once that 10 days is over. In this example, goods coming in on the first day of "shut down" would be delayed exactly 10 days, goods coming in on the third day would be delayed by exactly 8 days, etc. Goods coming in as the port re-opens would have no additional delay. In this example, this single event would increase the total yearly supply chain costs by 0.24%. In fact, this simple example is likely an underestimation of the effect a true shut down would have at a port. It is unlikely that all goods would be able to be cleared immediately when the port re-opens, and thus we would expect that capacity issues would cause lingering after-effects as the labor at the port catches up to the imports that have been delayed. If we were instead to spread that 10-day shut down such that the delay reduces back to zero over the course of a month after the port re-opens, this single event would increase the total yearly supply chain costs by 0.94%.

This total supply chain increase in cost increases linearly in the time it takes for the port operations to return to normal. However, as the length of the shock increases, the cost increases grow super-linearly. If the shock were to last 20 days instead of 10 days, even if all goods clear immediately, the cost increase to the supply chain would be 0.94%. If it would take an additional month to clear the goods from the shock, the cost increase to the supply chain would be 2.35%.

8.2. Allowing a Single Additional Port

We now would like to examine the cost increases when we allow a retailer to open a single additional port for use in their trans-loading strategy. We will also allow retailers to revert to a Direct shipping strategy, if that generates the optimal cost as the delay through LA-LB increases.
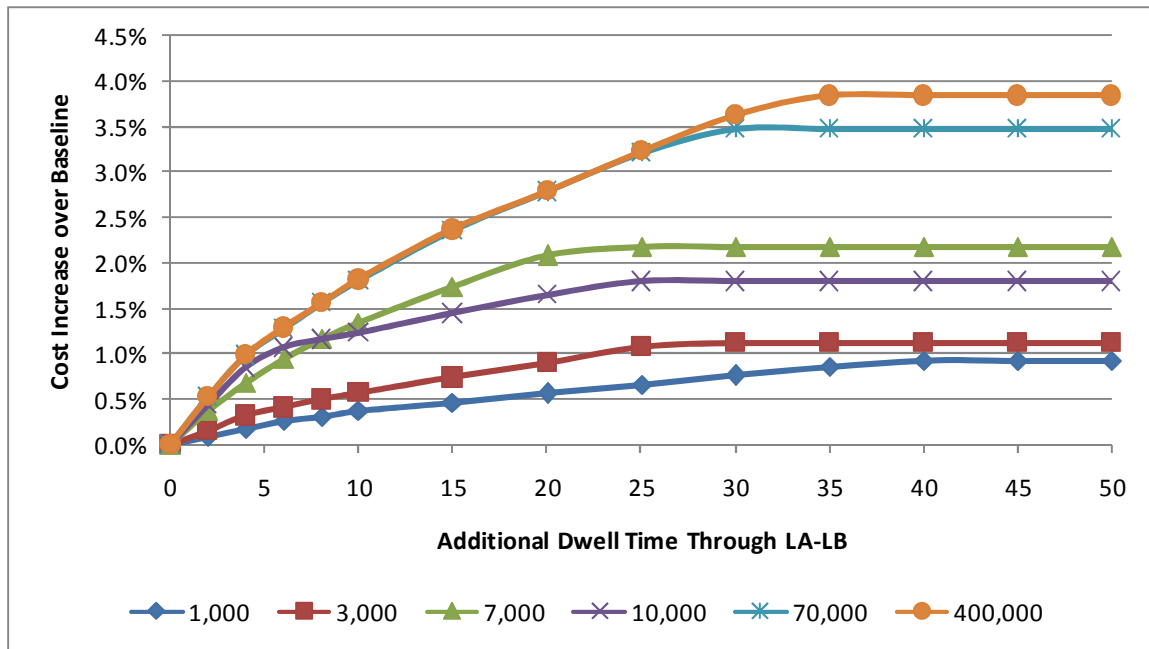
Figure 8-6. Cost Increase Due to Disruption for Sample Retailers with $5 Good Valuation, Allowing a Single Additional Port for Trans-load Usage

As we would expect, the cost increases do not change for the retailers that use the Direct shipping strategy for their baseline. This change will only affect retailers who previously used the TL-5 baseline strategy. For those retailers that do use a Trans-loading strategy at five ports for their baseline, we see them reduce their cost increases by reverting to a Direct shipping strategy. While we had previously seen these trans-loading retailers have a maximum cost increase of between 4% and 5%, we now see that the smaller retailers have a maximum increase of only about 2%, and the larger retailers have a maximum increase of between 3.5% and 4%. The smaller retailers will have a larger trans-loading less-than-container round-up factor than the larger retailers and thus will see a greater benefit from reverting to a Direct strategy.

Figure 8-7. Cost Reduction from Locked Strategy to Allowing a Single Additional Port for Trans-load Usage for Sample Retailers with $5 Good Valuation

We see that each of the trans-loading retailers with $5 per cubic foot goods valuation deviates from their baseline strategy to Direct shipping at a certain point so as to take advantage of the lower less-than-container round-up factor for marine containers.

For more expensive goods, we have the opportunity to see the cost reductions as a retailer opens additional ports for use in trans-loading strategies. We will start with goods with a $10 per cubic foot declared value, and show how their optimal strategies change as the delay at LA-LB increases.

Table 8-1. Optimal Strategy for Sample Retailers with $10 Good Valuation
at Increasing Delays through the Ports of LA-LB

Import Volume		1,000	3,000	7,000	10,000	70,000	400,000
Baseline Strategy		Direct	TL-5	TL-5	TL-4	TL-3-Sav	TL-WC
Delay	2	Direct	TL-5	TL-5	TL-5	TL-4	TL-3-Sav
	4	Direct	TL-5	TL-5	TL-5	TL-4	TL-3-Sav
	6	Direct	TL-5	TL-5	TL-5	TL-4	TL-3-Sav
	8	Direct	TL-5	TL-5	TL-5	TL-4	TL-3-Sav
	10	Direct	TL-5	TL-5	TL-5	TL-4	TL-3-Sav
	15	Direct	TL-5	TL-5	TL-5	TL-4	TL-3-Sav
	20	Direct	TL-5	TL-5	TL-5	TL-4	TL-3-Sav
	25	Direct	Direct	TL-5	Direct	TL-4	TL-3-Sav
	30	Direct	Direct	TL-5	Direct	TL-4	TL-3-Sav
	35	Direct	Direct	Direct	Direct	TL-3-Sav	TL-3-Sav
	40	Direct	Direct	Direct	Direct	TL-3-Sav	TL-3-Sav
	45	Direct	Direct	Direct	Direct	TL-3-Sav	TL-3-Sav
	50	Direct	Direct	Direct	Direct	TL-3-Sav	TL-3-Sav

For the retailers with import volumes between 3,000 and 7,000 TEUs per year, we see a reversion to a Direct strategy at a large enough LA-LB delay. The baseline optimal strategy for the retailer with a 10,000 TEU volume is to trans-load at four ports. We see that opening the fifth port to trans-loading, Houston in this case, has an immediate benefit for this retailer as the LA-LB delay increases. We also see that it too will eventually shift to a Direct shipping strategy to take advantage of the lower less-than-container round-up factor. The retailer with a 70,000 TEU volume shows an interesting pattern. Its baseline strategy is to trans-load at three ports: LA-LB, Seattle and Savannah. When facing a delay at LA-LB, it sees an immediate benefit by opening a fourth port: NY-NJ. However, when the LA-LB delay grows to a large enough level, this retailer will no longer allocate any RDCs to LA-LB, and its optimal strategy will be to consolidate at only Seattle and Savannah. That is, at a certain delay, the optimal strategy will only use ports available in the baseline strategy. There will be no additional benefit to opening an additional port to trans-loading volume. However, delays of this magnitude are unlikely to occur.

Figure 8-8. Cost Increase Due to Disruption for Sample Retailers with $10 Good Valuation, Allowing a Single Additional Port for Trans-load Usage
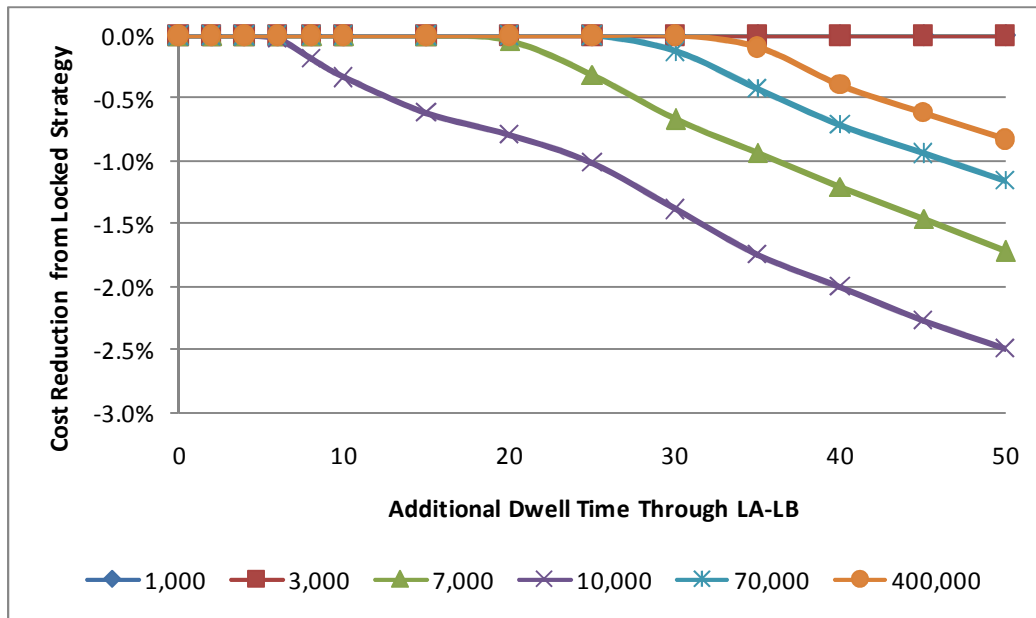
60

Figure 8-9. Cost Reduction from Locked Strategy to Allowing a Single Additional Port for Trans-load Usage for Sample Retailers with $10 Good Valuation

The reductions in the cost increases are the most notable at the point where a retailer transitions to Direct shipping. The addition of the fourth port for the 70,000 TEU retailer or the third port for the 400,000 TEU retailer reduces those cost increases by a negligible amount. The addition of the fifth port for the 10,000 TEU retailer shows a greater benefit, though still not substantial. We would expect that adding ports has marginal benefits. For a baseline strategy with more available ports, adding additional ports does not show benefits as great.

For retailers with greater declared goods values, we see usage of LA-LB drops with greater delays, but generally without the need to add more ports. For the $20 per cubic foot declared goods value retailers, we see the following set of strategies for LA-LB delays.

Table 8-2. Optimal Strategy for Sample Retailers with $20 Good Valuation
at Increasing Delays through the Ports of LA-LB

Import Volume		1,000	3,000	7,000	10,000	70,000	400,000
Baseline Strategy		Direct	TL-5	TL-4	TL-3-Sav	TL-WC	TL-WC
Delay	**2**	Direct	TL-5	TL-4	TL-3-Sav	TL-WC	TL-WC
	4	Direct	TL-5	TL-4	TL-3-Sav	TL-WC	TL-WC
	6	Direct	TL-5	TL-4	TL-3-Sav	TL-WC	TL-WC
	8	Direct	TL-5	TL-5	TL-3-Sav	TL-WC	TL-WC
	10	Direct	TL-5	TL-5	TL-3-Sav	TL-WC	TL-WC
	15	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea
	20	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea
	25	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea
	30	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea
	35	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea
	40	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea
	45	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea
	50	Direct	TL-5	TL-5	TL-3-Sav	TL-Sea	TL-Sea

Only the 7,000 TEU retailer adds ports to its optimal strategy as the delay through LA-LB increases. All of the other retailers use the same set of ports but shift the allocations away from LA-LB until that port is no longer used. (TL-Sea is the strategy wherein all containers are trans-loaded at Seattle.) However, it is worthwhile to note that by using these strategies, these retailers are now very vulnerable if a shock were to occur at both LA-LB and Seattle, especially the 70,000 and 400,000 TEU retailers. This is not an unlikely occurrence. If the port of LA-LB were to face a labor strike or other shock, a substantial volume of imports from many retailers may abandon LA-LB for Seattle, and in the process cause an over-capacity shock to Seattle. After the over-capacity meltdown at LA-LB in 2004, many retailers sent more of their goods to Seattle in 2005, thus causing an over-capacity issue in Seattle. Although these events occurred a year apart, a shock at one port directly caused a shock at the other.
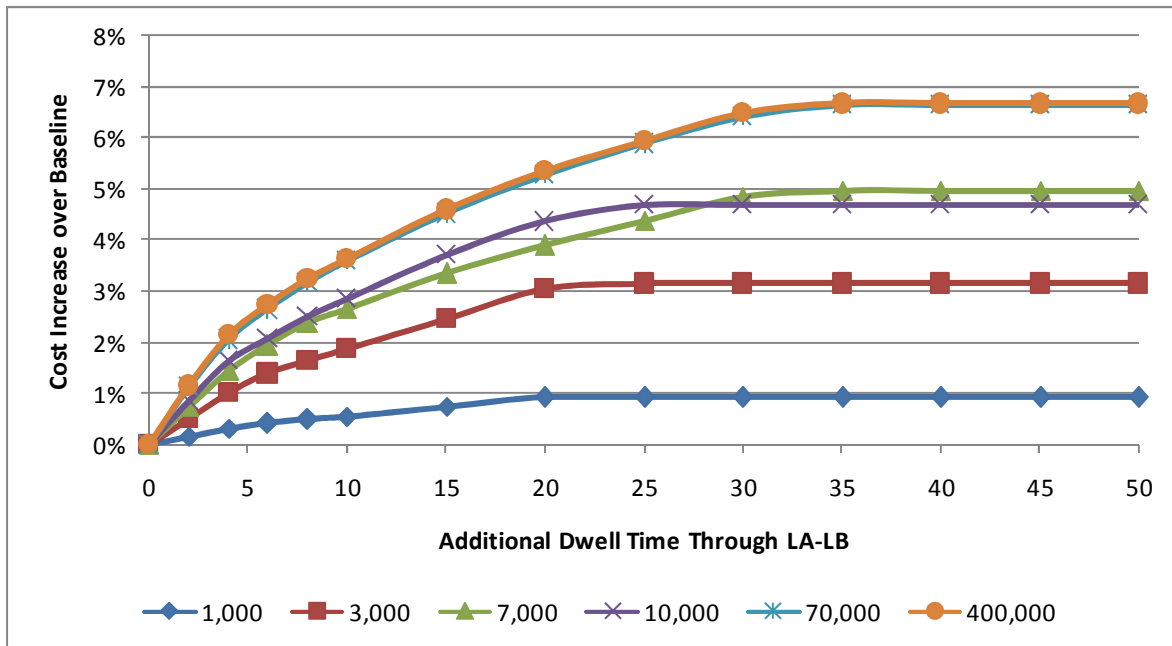
Figure 8-10. Cost Increase Due to Disruption for Sample Retailers with $20 Good Valuation, Allowing a Single Additional Port for Trans-load Usage
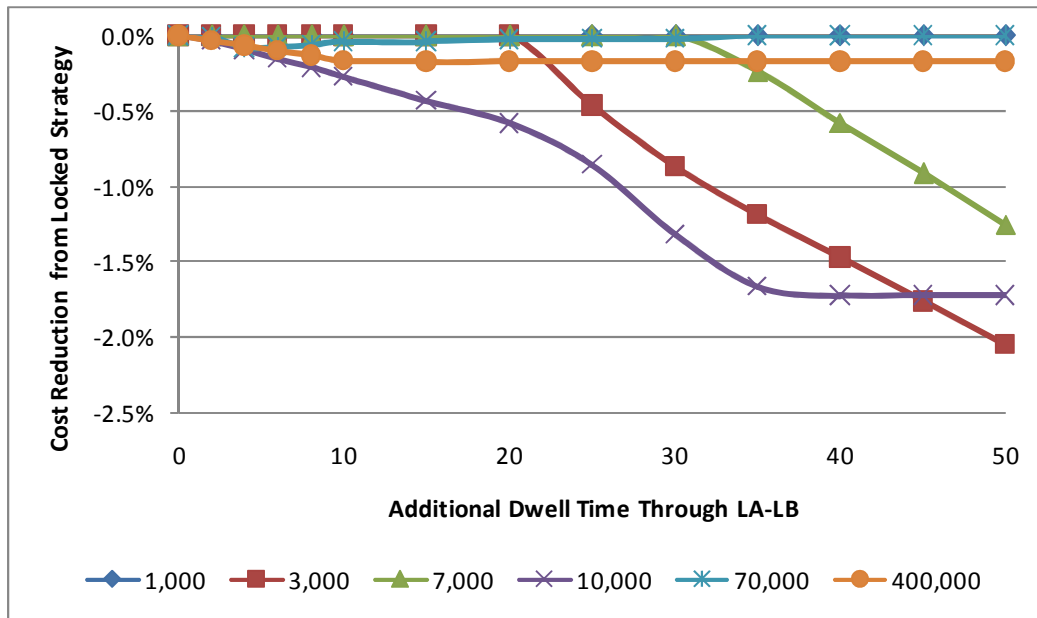

Figure 8-11. Cost Reduction from Locked Strategy to Allowing a Single Additional Port for Trans-load Usage for Sample Retailers with $20 Good Valuation

As we noted, only the 7,000 TEU retailer shows any additional benefit by adding ports to its optimal strategy. However, all of the other retailers become more vulnerable to additional shocks.

Lastly, we will examine the cases of retailers whose baseline optimal strategy is to trans-load at LA-LB only. We will examine the retailers with a declared goods value of $50 per cubic foot.

Table 8-3. Optimal Strategy for Sample Retailers with $50 Good Valuation
at Increasing Delays through the Ports of LA-LB

Import Volume		1,000	3,000	7,000	10,000	70,000	400,000
Baseline Strategy		TL-4	TL-3-Sav	TL-WC	TL-WC	TL-LA	TL-LA
Delay	2	TL-4	TL-3-Sav	TL-3-Sav	TL-WC	TL-WC	TL-WC
	4	TL-4	TL-3-Sav	TL-WC	TL-WC	TL-WC	TL-WC
	6	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	8	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	10	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	15	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	20	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	25	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	30	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	35	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	40	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	45	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea
	50	TL-5	TL-3-Sav	TL-3-Sav	TL-Sea	TL-Sea	TL-Sea

The 1,000 TEU and 7,000 TEU retailers do show a benefit by adding a port available for trans-loading as the delay through LA-LB grows, a fifth port for the 1,000 TEU retailer and a third port for the 7,000 TEU retailer. As is expected, the largest retailers do recommend adding Seattle as a second port as soon as the delay through LA-LB is greater than zero. We would expect to see a major reduction in the cost increases for these two retailers.
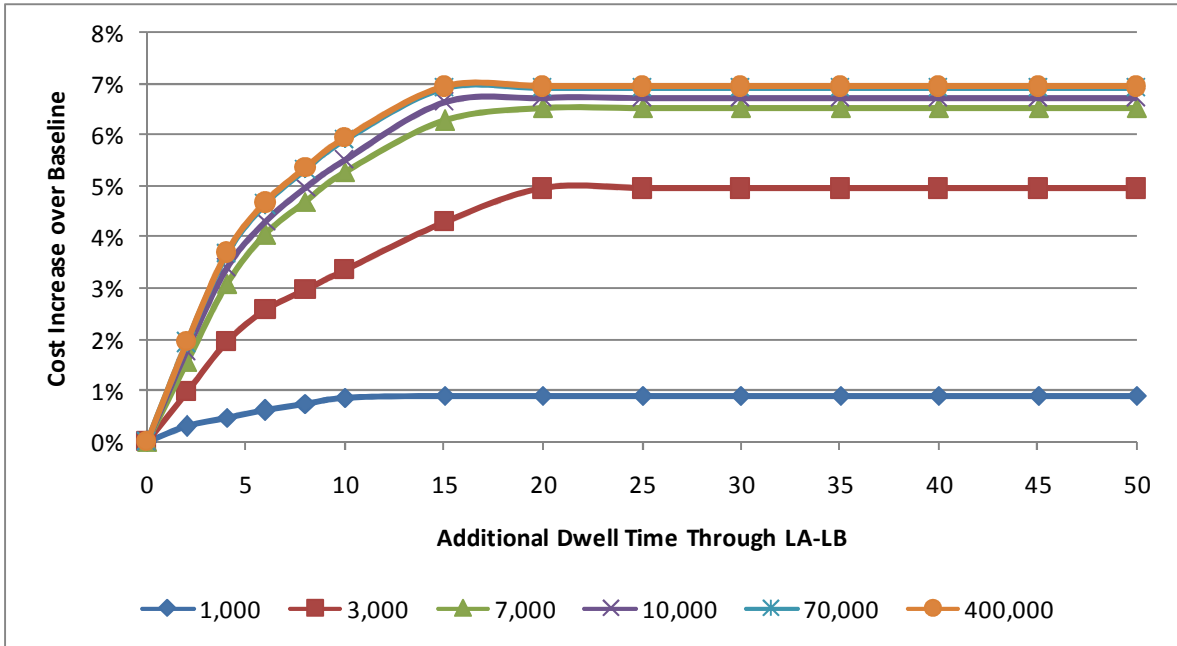

Figure 8-12. Cost Increase Due to Disruption for Sample Retailers with $50 Good Valuation, Allowing a Single Additional Port for Trans-load Usage
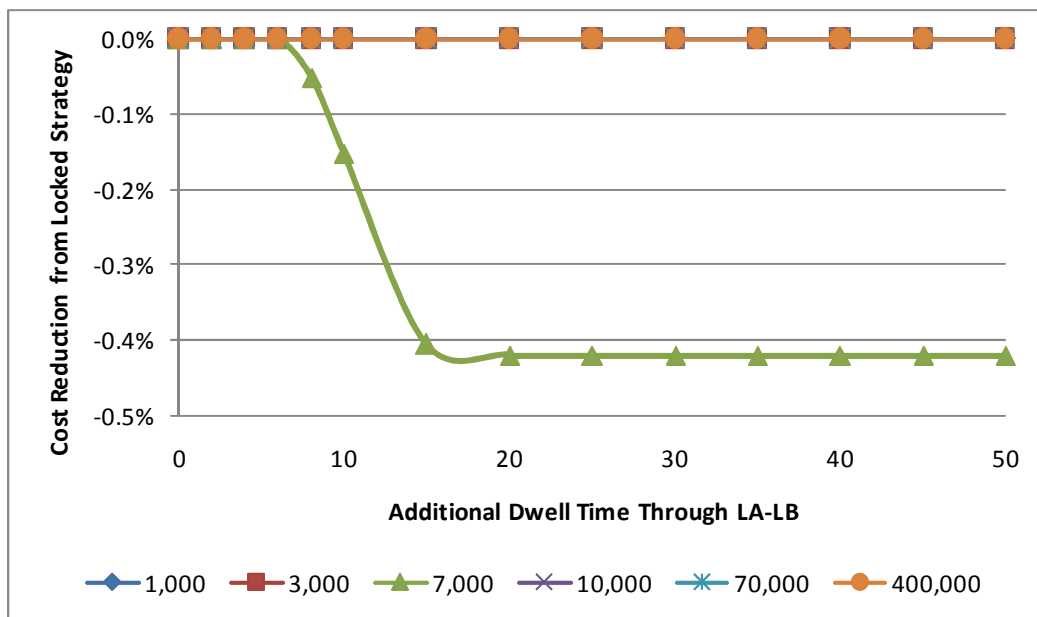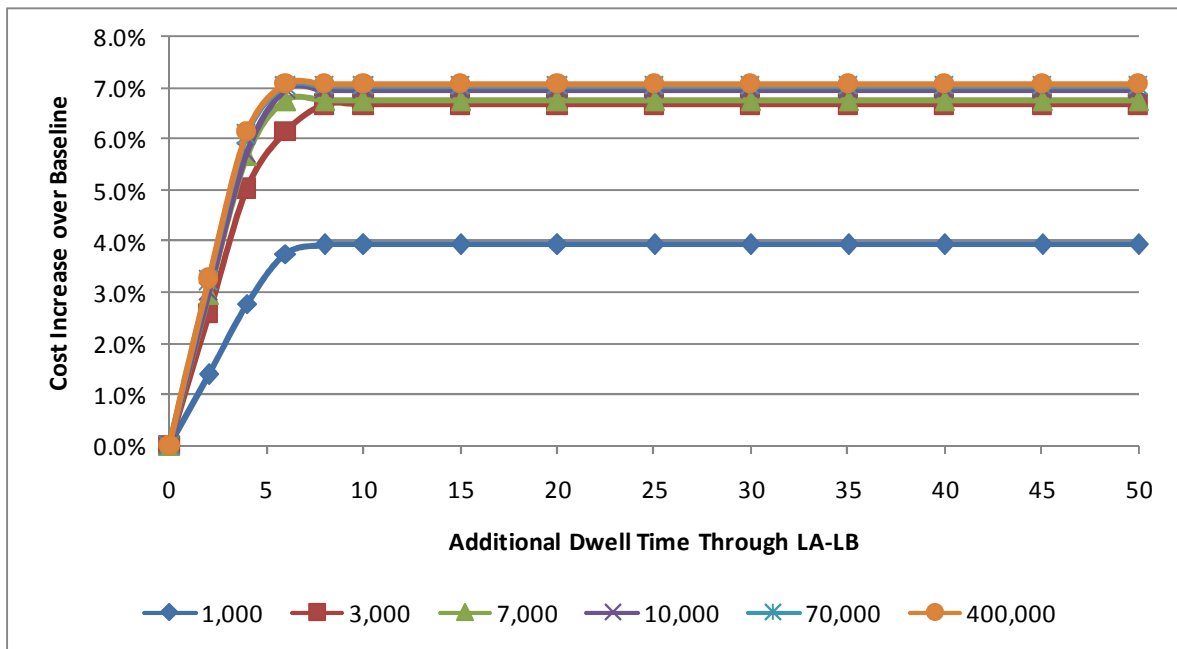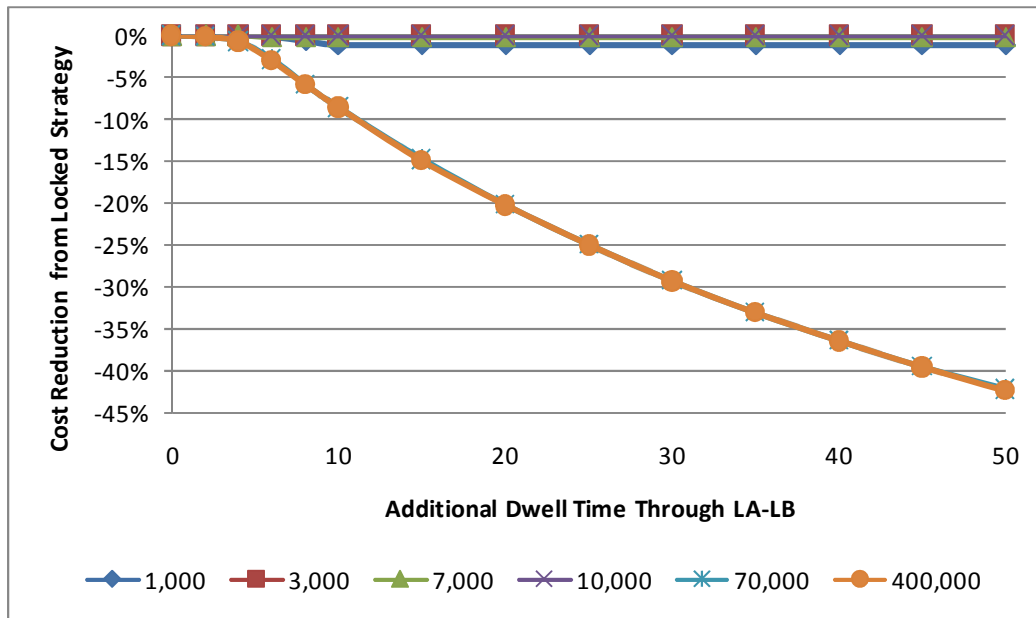
Figure 8-13. Cost Reduction from Locked Strategy to Allowing a Single Additional Port for Trans-load Usage for Sample Retailers with $50 Good Valuation

Now instead of the massive cost increases for the 70,000 and 400,000 TEU retailers, we at most see cost increases of approximately 7%, more in line with the cost increases seen for all of the other retailers who use two or more ports in their baseline optimal strategy. The addition of one more port for trans-loading substantially reduces the cost increase due to a shock for the retailers who rely solely on that one port.

Under this paradigm of adding additional ports, we can analyze the example from the previous section where the TL-LA retailer encounters the single event that causes LA-LB to be unavailable for exactly 10 days. Now, when the LA-LB port shuts down, goods can start transferring to a new port, instead of being required to face this delay. Under the assumption that goods clear immediately after the shut down ends, this single event would increase the total yearly supply chain costs by 0.15%. If we were instead to spread that 10-day shut down such that the delay through LA-LB reduces back to zero over the course of a month after the port re-opens, this event would increase the total yearly supply chain costs by 0.59%. This is a yearly cost reduction of 0.34% from the single shock case where the retailer is only able to use LA-LB.

If the shock were to increase to 20 days, the cost increase for the immediate clearing cost case would increase from 0.15% to 0.34%. The cost increase for the case where it takes the additional month to clear the goods would be 0.86%. This is a reduction of 1.5% from the single shock case where the retailer is only able to use LA-LB. As the length of the shock increases, there is more benefit can be derived from having a redundant port available for trans-loading operations.

We can also examine situations where we allow retailers to open more than one additional port for trans-loading operations. However, this seems to have no effect on the cost reduction in most cases, even with long shocks to LA-LB. There are very few combinations of declared good value and importing volume that do show any benefit by adding infrastructure to two or more ports, and the benefit over simply adding one port is negligible.

65

We can now examine the costs of adding trans-loading operations to a particular port and compare this to the cost savings in the case of shocks. Most operations specific to cross-docking and swapping cargo are run by third-party logistics companies, whose contractual costs will likely be similar at various ports around the country. The main cost associated with opening trans-loading operations will be that of leasing land for and building an import warehouse in the hinterland of that port. Depending on the yearly importing volume of the retailer, the size of the warehouse necessary for maintaining these operations will vary. For retailers with a yearly importing volume greater than 50,000 TEUs per year, these facilities may be anywhere between half a million and two million square feet. Based on information received from a land and property management company specializing in these operations, we found that construction costs at the hinterland of the port would likely be around $25 per square foot and total leasing costs (including utilities and tax) would be between $0.30 and $0.35 per square foot per year, depending on the age and efficiency of the building.

Thus, for the large retailers, building costs would be between $12.5 million and $50 million. Leasing costs would be between $150,000 and $700,000 per year. We can now compare this with the total costs of the supply chain operations for the various retailers to see how this compares to the benefits of opening a new port for trans-loading operations.

The $50 per cubic foot declared good value retailers with a yearly importing volume of 70,000 TEUs per year and greater were examples of retailers who used trans-loading only at LA-LB as their optimal strategy when there were no shocks causing additional delay at LA-LB. The yearly supply chain cost to the 70,000 TEU per year retailer is approximately $320 million per year, and the cost to the 400,000 TEU retailer is approximately $1.82 billion per year. If we assume normal operations over a year except for a single a 10 day shock with an additional month to clear goods as a baseline to compare against, we see that the 70,000 TEU retailer would save $1.1 million by expanding operations to a second port. The 400,000 TEU retailer would save $6.3 million by expanding to a second port. If we assume a 20 day shock with an additional month to clear goods, we see a cost savings of $4.8 million for the 70,000 TEU retailer and a cost savings of $27.3 million for the 400,000 TEU retailer. Given an appropriately sized warehouse for the retailer, the additional port acts as protection against cost increases caused by these shocks. As there is a comparatively low rental cost, the major downside of opening the second port is the initial building cost, which can also be mitigated through amortization. The retailer can consider this as insurance against these kinds of shocks.

For the retailers who already have at least two ports available for trans-loading, the cost protection against these shocks from an additional port of entry is negligible. We will use the retailers with a $10 per cubic foot declared good value as examples here. The 70,000 TEU retailer with $10 declared good value uses trans-loading at three ports as its baseline optimal strategy. The 400,000 TEU retailer uses trans-loading at two ports as its baseline optimal strategy. For the larger retailers, opening a third or fourth port saves no more than 0.02% of yearly cost even for the 20 day shock with an additional month to clear. This equates to a savings no greater than $200,000. Smaller retailers may see a slightly larger relative savings, but a similarly low absolute savings. As this would not even cover the cost of the rent on the import warehouse property, the additional insurance of the third or fourth port does not seem to be worthwhile investment for retailers whose baseline optimal strategy already includes at least two ports. It is again worthwhile to note this analysis only considers a shock to a single port without

considering the possibility of shocks to two ports at the same time, and does not take into account any negotiation benefits that the retailer can derive from third-party logistics providers at multiple ports.

We now see that most large importers design supply chains with more ports of entry than is deterministically optimal. We analyzed the value of such redundancy in terms of cost avoidance should there be a temporary disruption to imports at the Ports of Los Angeles and Long Beach. Our analysis suggests that only modest gains are available from such redundancy, probably not enough to justify the redundant investment. We are left with the conclusion that an increased position of power in negotiations with transportation carriers, third-party logistics operators, and landlords must be a more prominent justification for redundancy as it is actually practiced. It is also conceivable that the use of these additional ports is due to the regional history of a retailer, previous to when its operations became truly national.

9. Conclusions and Further Studies

In this dissertation, we proposed a heuristic algorithm and shortest path model for the optimization of the supply chains of importers of waterborne containerized goods from Asia to USA. This optimization model determines the set of least-cost supply chain strategies for an importer, in terms of ports and landside channels to be used for each set of goods. The costs considered include costs for transportation and handling, pipeline inventory, and safety stock inventory at RDCs. We then showed how the optimal strategy for each set of goods can be combined into an optimal set of importing strategies.

In general, use of the trans-loading channels entails a premium in terms of transportation and handling charges over the costs for direct shipping. These extra transportation costs must be traded off against potential inventory savings afforded by pooling shipments to multiple regional destinations over the segment of the supply chain between Asia and the trans-loading warehouse. Therefore, the best strategy for low-value goods can be quite different from the best strategy for high-value goods. Our study shows that for high-value goods, such consolidation-deconsolidation supply chain strategies are attractive; for low-value goods, much less so. Moreover, to achieve the least total cost, the set of trans-loading strategies must be tailored according to the value of the goods. For very-high-value goods, consolidating replenishment of all Continental USA RDCs via Los Angeles-Long Beach is most efficient. For medium-value goods, it is more efficient to practice a policy of trans-loading at multiple ports. For the lower medium-value goods, the policy will likely include at least one East Coast port, while for the higher medium-value goods, the policy will likely use only West Coast ports.

We examined how to capture value from a multiple strategy supply chain. The cost reduction for multi-strategy is heavily dependent on the transportation rate and lead time parameters as well as the goods valuation distribution for the retailer. The largest cost reductions can be achieved by splitting goods into a set that will be imported via a Direct shipping strategy and a set that will be imported via a Trans-loading strategy. An additional cost reduction can be attained by splitting out the most expensive goods into a set that will be imported via Trans-loading at a single port only; in our case, that port will be Los Angeles-Long Beach. The cost reductions resulting from splitting between different strategies that Trans-load at multiple ports will be negligible and will almost certainly not outweigh the overhead costs to the retailer of

implementing an additional importing strategy. Our analysis of Customs data indicates that there are between 10 and 40 retailers in the United States that can take advantage of multi-strategy supply chains, though we do not have access to the complete data, including third-party logistics negotiated costs and goods valuation distributions, to narrow that number down further.

We also analyzed the value of building redundancy into the importing supply chain. We noted that many retailers seem to utilize more ports for trans-loading than we would consider optimal. We found that having access to at least two ports for trans-loading will almost certainly be of value, so as to prevent a major cost increase in the case of a disruption or shock at any single port. However, we do not see a clear need for additional ports for disruption mitigation, if the optimal strategy recommended already uses at least two ports for trans-loading operations. We thus conclude that there must be a non-operational reason that many retailers use additional ports. Our hypothesis is that retailers gain negotiating leverage with their third-party logistics partners and transportation providers by utilizing these additional ports. There may also be a historical inertia component, in that some retailers may not want to modify or eliminate their operations in a given port location once infrastructure has been built nearby.

There are several directions to pursue for further research on this topic. First, one could examine contractual terms and obligations at various points along the supply chain. In the simplest case, importers may have contractual requirements for volumes by port or channel. Additionally, there could exist a fixed cost for any utilization of a particular port. Another example could be penalties imposed by railroads for imbalances in container flows. That is, there could be penalties imposed on the beneficial cargo owners of steamship lines if the number of containers outgoing from a port is not equal to the number of containers incoming (for exporting purposes). When this is the case, the railroads would likely have to send empty containers from point to point to maintain a reasonable steady state, and they may be able to collect fees from the beneficial cargo owners to handle these additional costs that they must carry.

For many importers the supply chain strategies over a given year are not homogeneous. Some importers may have one-off specials, i.e. seasonal or holiday items that are only in stores for a short time, and may require special handling along the supply chain. Some importers may be able to take advantage of a different set of strategies at different times of the year. There may additionally be capacity limits for different supply chain channels. In this case, it may be worthwhile to study the excess capacities at different times of the year, when the import volume is lower.

To better account for the smaller retailers, we could expand the model so that it allows for a different review interval. If we were to modify the review interval, the cost of cycle inventory would have to be added to the objective function.

In addition to transportation and inventory costs, the proposed model could be further expanded to include other parameters such as environmental impact factors. The efficiency and effectiveness of different models of the cost of environmental impact could be further studied under various scenarios.

References

Ahuja, R.K., Magnanti, T.L., Orlin, J.B. 1993. *Network Flows.* Prentice-Hall Inc.

Ambrosino, D., Scutellà, M.G., 2005. Distribution network design: New problems and related models. European Journal of Operational Research 165 (3), 610 – 624.

Bollapragada, R., Akella, R. Srinivasan, R., 1998. Centralized ordering and allocation policies in a two-echelon system with non-identical warehouses. European Journal of Operational Research 106 (1), 74-81.

Caris, A., Macharis, C., Janssens, G.K., 2008. Planning problems in intermodal freight transport: Accomplishments and prospects. Transportation Planning and Technology 31 (3), 277-302.

Chakravarty, A. K., Orlin, J. B., Rothblum, U. G., 1982. A Partitioning Problem with Additive Objective with an Application to Optimal Inventory Groupings for Joint Replenishment. Operations Research 30 (5), 1018-1022.

Chakravarty, A.K., Orlin, J.B., Rothblum, U.G., 1985. Consecutive Optimizers for a Partitioning Problem with Applications to Optimal Inventory Groupings for Joint Replenishment. Operations Research 33 (4), 820-834.

Chopra, S., Sodhi, M., 2004. Managing Risk To Avoid Supply-Chain Breakdown. Sloan Management Review, 46 (1), 53–62.

Christopher, M., Peck, H., 2004. Building the Resilient Supply Chain. International Journal of Logistics Management, Vol. 15 Iss: 2, 1 - 14.

Cordeau, J.F., Pasin, F., Solomon, M.M., 2006. An integrated model for logistics network design. Annals of Operations Research 144 (1), 59–82.

Cui, T., Ouyang, Y., and Shen, Z.-J.M., 2010. Reliable facility location design under the risk of disruptions. Operations Research, 58 (1-Part 4), 998-1011.

Daskin, M.S., Coullard, C., Shen, Z.-J., 2002. An inventory-location model: formulation, solution algorithm and computational results. Annals of Operations Research 110 (1-4), 83–106.

Davidson, E.T., Leachman, R.C. 2012. Optimizing a Multi-Strategy Port and Modal Allocation of Containerized Imports from Asia to the United States. Journal of Marketing Channels. 19 (2), 120-140.

Eppen, G., 1979. Effects of centralization on expected costs in multi-location newsboy problem. Management Science 25 (5), 498-501.

Eppen, G., Schrage, L., 1981. Centralized ordering policies in a multi-warehouse system with lead times and random demand. In: Schwarz, L.B. (Ed.), Multi-Level Production/Inventory Control Systems: Theory and Practice. North Holland, pp. 51–68.

Erlebacher, S.J., Meller, R.D., 2000. The interaction of location and inventory in designing distribution systems. IIE Transactions 32 (2), 155–166.

Jula, P., Leachman, R.C., 2011. Long- and Short-Run Supply-Chain Optimization Models for the Allocation and Congestion Management of Containerized Imports from Asia to the United States. Transportation Research Part E 47 (5), 593-608.

Leachman, R. C., 2008. Port and Modal Allocation of Waterborne Containerized Imports from Asia to the United States. Transportation Research Part E 44 (2), 313 – 331.

Lim, M., Daskin, M. S., Bassamboo, A. and Chopra, S. (2010), A facility reliability problem: Formulation, properties, and algorithm. Naval Research Logistics, 57: 58–70.

Liu, S.C., Lin, C.C., 2005. A heuristic method for the combined location routing and inventory problem. International Journal of Advanced Manufacturing Technology 26 (4), 372-381.

Ma, H.Z., Davidrajuh, R., 2005. An iterative approach for distribution chain design in agile virtual environment. Industrial Management and Data Systems 105 (5-6), 815–834.

Manzini, R., Bindi, F., 2009. Strategic design and operational management optimization of a multi stage physical distribution system. Transportation Research Part E 45 (6), 915–936.

Melo, M.T., Nickel, S., Saldanha-da-Gama F., 2009. Facility location and supply chain management – A review. European Journal of Operational Research 196 (2), 401–412.

Miranda, P.A., Garrido, R.A., 2004. Incorporating inventory control decisions into a strategic distribution network design model with stochastic demand. Transportation Research Part E 40 (3), 183–207.

ReVelle, C.S., Eiselt, H.A., Daskin, M.S., 2008. A bibliography for some fundamental problem categories in discrete location science. European Journal of Operational Research 184 (3), 817–848.

Shen, Z.-J., 2007. Integrated Supply Chain Design Models: An Survey and Future Research Directions. Journal of Industrial and Management Optimization 3 (1), 1–27.

Shen, Z.-J., Coullard, C., Daskin, M.S., 2003. A joint location-inventory model. Transportation Science 37 (1), 40–55.

Shen, Z.-J., Qi, L., 2007. Incorporating inventory and routing costs in strategic location models. European Journal of Operational Research 179 (2), 372– 389.

Shu, J., Teo, C.P., Shen, Z.-J., 2005. Stochastic transportation-inventory network design problem. Operations Research 53 (1), 48–60.

Silver, E.A., Peterson, R., 1985. Decision Systems for Inventory Management and Production Planning. John Wiley and Sons.

Snyder, L.V., 2006. Facility location under uncertainty: A review. IIE Transactions, 38, 537–554.

Snyder, L.V., Daskin M.S., 2005. Reliability models for facility location: The expected failure cost case. Transportation Science 39, 400-416.

Snyder, L.V., Daskin, M.S., Teo, C.P., 2007. The stochastic location model with risk pooling. European Journal of Operational Research 179 (3), 1221–1238.

Snyder, L.V., Scaparra, M.P., Daskin, M.L., Church, R.C, Johnson, M. P., Norman, B. and Secomandi, N., 2006. Planning for disruptions in supply chain networks. TutORials in Operations Research, INFORMS, Baltimore, 234-257.

You, F., Grossmann, I.E., 2008. Mixed-Integer Nonlinear Programming models and algorithms for large-scale supply chain design with stochastic inventory management. Industrial & Engineering Chemistry Research 47 (20), 7802-7817.

Wilhelm, W., Liang, D., Rao, B., Warrier, D., Zhu, X., Bulusu, S., 2005. Design of international assembly systems and their supply chains under NAFTA. Transportation Research Part E 41 (6), 467–493.

Appendix A. Anomalous RDC-Port Assignments for the Case Study Retailer

Table A-1. Original Heuristic – RDC-Port Assignment for the Case Study Retailer – $150 LA-LB Wharfage Fee

RDC	Strategy = TL-LA	Fee = $150		Strategy = TL-4	Fee = $150	
	Land Transport Mode	Lowest Trans + Pipe Cost Port	Cost	Land Transport Mode	Lowest Trans + Pipe Cost Port	Cost
Seattle-Tacoma	TL Rail 53	LA-Long Beach	$110,660	Direct Dray	Seattle-Tacoma	$88,855
Oakland	TL Truck 53	LA-Long Beach	$159,248	TL Truck 53	LA-Long Beach	$160,062
LA-Long Beach	Direct Dray	LA-Long Beach	$233,371	Direct Dray	LA-Long Beach	$235,245
Dallas	TL Rail 53	LA-Long Beach	$128,158	TL Rail 53	LA-Long Beach	$128,561
Houston	TL Rail 53	LA-Long Beach	$162,723	TL Rail 53	LA-Long Beach	$163,271
Memphis	TL Rail 53	LA-Long Beach	$108,241	TL Rail 53	LA-Long Beach	$108,525
Kansas City	TL Rail 53	LA-Long Beach	$118,830	TL Rail 53	LA-Long Beach	$119,186
Minneapolis	TL Rail 53	LA-Long Beach	$102,647	TL Rail 53	Seattle-Tacoma	$97,994
Chicago	TL Rail 53	LA-Long Beach	$310,681	TL Rail 53	LA-Long Beach	$312,222
Cleveland	TL Rail 53	LA-Long Beach	$115,612	TL Rail 53	LA-Long Beach	$115,888
Columbus	TL Rail 53	LA-Long Beach	$58,527	TL Rail 53	LA-Long Beach	$58,617
Pittsburgh	TL Rail 53	LA-Long Beach	$87,330	TL Rail 53	LA-Long Beach	$87,485
Atlanta	TL Rail 53	LA-Long Beach	$218,525	TL Rail 53	LA-Long Beach	$219,246
Savannah	TL Rail 53	LA-Long Beach	$93,217	Direct Dray	Savannah	$99,632
Charleston	TL Rail 53	LA-Long Beach	$22,006	TL Rail 53	LA-Long Beach	$22,019
Charlotte	TL Rail 53	LA-Long Beach	$105,824	TL Rail 53	LA-Long Beach	$106,017
Harrisburg	TL Rail 53	LA-Long Beach	$72,644	TL Rail 53	LA-Long Beach	$72,750
Norfolk	TL Rail 53	LA-Long Beach	$95,504	TL Rail 53	LA-Long Beach	$95,646
Baltimore	TL Rail 53	LA-Long Beach	$96,126	TL Rail 53	LA-Long Beach	$96,293
NY-NJ	TL Rail 53	LA-Long Beach	$369,061	Direct Dray	NY-NJ	$380,624
Boston	TL Rail 53	LA-Long Beach	$148,523	TL Rail 53	LA-Long Beach	$148,833
Total			$2,917,459			$2,916,971

Table A-2. Original Heuristic – RDC-Port Assignment for the Case Study Retailer – $200 LA-LB Wharfage Fee

RDC	Strategy = TL-LA	Fee = $200		Strategy = TL-4	Fee = $200	
	Land Transport Mode	Lowest Trans + Pipe Cost Port	Cost	Land Transport Mode	Lowest Trans + Pipe Cost Port	Cost
Seattle-Tacoma	TL Rail 53	LA-Long Beach	$111,612	Direct Dray	Seattle-Tacoma	$79,757
Oakland	TL Truck 53	LA-Long Beach	$160,817	TL Truck 53	LA-Long Beach	$163,882
LA-Long Beach	Direct Dray	LA-Long Beach	$236,159	Direct Dray	LA-Long Beach	$243,119
Dallas	TL Rail 53	LA-Long Beach	$129,240	TL Rail 53	LA-Long Beach	$130,806
Houston	TL Rail 53	LA-Long Beach	$164,042	TL Rail 53	LA-Long Beach	$166,157
Memphis	TL Rail 53	LA-Long Beach	$109,132	TL Rail 53	LA-Long Beach	$110,246
Kansas City	TL Rail 53	LA-Long Beach	$119,829	TL Rail 53	LA-Long Beach	$121,215
Minneapolis	TL Rail 53	LA-Long Beach	$103,419	TL Rail 53	Seattle-Tacoma	$91,503
Chicago	TL Rail 53	LA-Long Beach	$313,282	TL Rail 53	Seattle-Tacoma	$321,052
Cleveland	TL Rail 53	LA-Long Beach	$116,513	TL Rail 53	Seattle-Tacoma	$117,862
Columbus	TL Rail 53	LA-Long Beach	$58,974	TL Rail 53	Seattle-Tacoma	$59,377
Pittsburgh	TL Rail 53	LA-Long Beach	$87,958	TL Rail 53	Seattle-Tacoma	$88,688
Atlanta	TL Rail 53	LA-Long Beach	$220,162	TL Rail 53	LA-Long Beach	$222,941
Savannah	TL Rail 53	LA-Long Beach	$93,883	Direct Dray	Savannah	$99,632
Charleston	TL Rail 53	LA-Long Beach	$22,147	TL Rail 53	LA-Long Beach	$22,201
Charlotte	TL Rail 53	LA-Long Beach	$106,586	TL Rail 53	LA-Long Beach	$107,355
Harrisburg	TL Rail 53	LA-Long Beach	$73,155	TL Rail 53	Seattle-Tacoma	$73,633
Norfolk	TL Rail 53	LA-Long Beach	$96,152	TL Rail 53	Seattle-Tacoma	$96,807
Baltimore	TL Rail 53	LA-Long Beach	$96,805	TL Rail 53	Seattle-Tacoma	$97,595
NY-NJ	TL Rail 53	LA-Long Beach	$371,719	Direct Dray	NY-NJ	$380,624
Boston	TL Rail 53	LA-Long Beach	$149,538	TL Rail 53	Seattle-Tacoma	$151,059
Total			$2,941,127			$2,945,510

Table A-3. Improved Heuristic – RDC-Port Assignment for the Case Study Retailer – New Lowest Cost
Assignment for both the $150 and $200 LA-LB Wharfage Fees

RDC	Strategy = TL-4		Fee = $150	Strategy = TL-4		Fee = $200
	Land Transport Mode	Lowest Trans + Pipe Cost Port	Cost	Land Transport Mode	Lowest Trans + Pipe Cost Port	Cost
Seattle-Tacoma	Direct Dray	Seattle-Tacoma	$88,855	Direct Dray	Seattle-Tacoma	$88,855
Oakland	TL Truck 53	LA-Long Beach	$159,490	TL Truck 53	LA-Long Beach	$161,059
LA-Long Beach	Direct Dray	LA-Long Beach	$233,930	Direct Dray	LA-Long Beach	$236,718
Dallas	TL Rail 53	LA-Long Beach	$128,276	TL Rail 53	LA-Long Beach	$129,358
Houston	TL Rail 53	LA-Long Beach	$162,884	TL Rail 53	LA-Long Beach	$164,204
Memphis	TL Rail 53	LA-Long Beach	$108,325	TL Rail 53	LA-Long Beach	$109,216
Kansas City	TL Rail 53	LA-Long Beach	$118,935	TL Rail 53	LA-Long Beach	$119,933
Minneapolis	TL Rail 53	Seattle-Tacoma	$97,994	TL Rail 53	Seattle-Tacoma	$97,994
Chicago	TL Rail 53	LA-Long Beach	$311,138	TL Rail 53	LA-Long Beach	$313,739
Cleveland	TL Rail 53	LA-Long Beach	$115,693	TL Rail 53	LA-Long Beach	$116,594
Columbus	TL Rail 53	LA-Long Beach	$58,554	TL Rail 53	LA-Long Beach	$59,000
Pittsburgh	TL Rail 53	LA-Long Beach	$87,375	TL Rail 53	LA-Long Beach	$88,003
Atlanta	TL Rail 53	LA-Long Beach	$218,738	TL Rail 53	LA-Long Beach	$220,374
Savannah	TL Rail 53	LA-Long Beach	$93,262	TL Rail 53	LA-Long Beach	$93,928
Charleston	TL Rail 53	LA-Long Beach	$22,010	TL Rail 53	LA-Long Beach	$22,151
Charlotte	TL Rail 53	LA-Long Beach	$105,881	TL Rail 53	LA-Long Beach	$106,643
Harrisburg	TL Rail 53	LA-Long Beach	$72,675	TL Rail 53	LA-Long Beach	$73,186
Norfolk	TL Rail 53	LA-Long Beach	$95,545	TL Rail 53	LA-Long Beach	$96,194
Baltimore	TL Rail 53	LA-Long Beach	$96,175	TL Rail 53	LA-Long Beach	$96,854
NY-NJ	TL Rail 53	LA-Long Beach	$369,517	TL Rail 53	LA-Long Beach	$372,175
Boston	TL Rail 53	LA-Long Beach	$148,614	TL Rail 53	LA-Long Beach	$149,629
Total			$2,893,866			$2,915,808

Appendix B. Approximated Single Import Strategy for Case Study Retailer

RDC	Port of Entry
Pueblo, CO	Seattle
Cedar Falls, IA	Seattle
Dekalb, IL	Los Angeles-Long Beach
Indianapolis, IN	Los Angeles-Long Beach
Kalamazoo, MI	Los Angeles-Long Beach
Fridley, MN	Seattle
West Jefferson, OH	Los Angeles-Long Beach
Oconomowoc, WI	Seattle
Wilton/Amsterdam, NY	Seattle
Chambersburg, PA	Seattle
Stuarts Draft, VA	Savannah/Norfolk
Albany, OR	Seattle
Phoenix, AZ	Los Angeles-Long Beach
Fontana/Rialto, CA	Los Angeles-Long Beach
Woodland, CA	Los Angeles-Long Beach
Shafter, CA	Los Angeles-Long Beach
Huntsville, AL	Los Angeles-Long Beach
Tifton, GA	Savannah/Norfolk
Midway, GA	Savannah/Norfolk
Newton, NC	Savannah/Norfolk
Lugoff, SC	Savannah/Norfolk
Tyler, TX	Los Angeles-Long Beach
Midlothian, TX	Los Angeles-Long Beach
Topeka, KS	Los Angeles-Long Beach