Facility Location and Transportation in Two Free Trade Zones

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In any supply chain, the location of facilities and the routing of material are important decisions that contribute a significant amount of costs, lowering a corporation's overall profits. These choices become more important when dealing with a global supply chain, whose players span multiple countries and continents. International factors, such as tax rates and transfer prices, must be carefully considered, while the advantages of timely delivery versus cost-effective transportation must be carefully weighed to ensure that customer demands are met at the best possible price.

We examine an international supply chain with plants, distribution centers (DCs), and customers in the North American Free Trade Agreement (NAFTA) and the European Union (EU) regions. The company in question manufactures two sub-assemblies at its plant in Mexico, and then assembles them into a final product at DCs in North America and Europe. To better serve its European customers, the company wishes to locate a new plant in the EU, as well as determine the modes of transportation used to distribute products between nodes, while maximizing overall profit.

The problem is formulated as a mixed integer linear program and is solved in two stages using a Strategic Model (SM) and an Operational Model (OM). In SM, each time period represents one month and we determine the optimal facility locations over a 12-month time horizon. With transportation lead times expressed in days, we can be certain that demand will be fulfilled within a single period, and for this reason, lead times are not considered in SM. At the operational level, however, each time period represents one day, and so lead times must be included as they will affect the choice of mode for a given route. The location results from SM are used as input for OM, which then gives the optimal modal and routing decisions for the network.

A number of cases are tested to determine how the optimal network is affected by changes in fixed and variable costs of facilities, transfer prices charged by plants to DCs, and the differing tax rates of each country.

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

In any industry, a supply chain describes how a product moves from a supplier to a customer, with value added along the way. Whether it be a cell phone, car, pair of shoes, or box of cereal, every end item begins with a collection of raw materials sourced from a supplier. A manufacturer then uses a variety of processes to transform the materials into components and modules, and eventually they are assembled into the final product, ready for shipment to customers.

For local or domestic supply chains, typical decisions to be made include determining the set of suppliers, how many products to produce, which plants will serve which customers, and the routes by which material is transported from one location to another. For global supply chains, these same decisions apply, but one must also consider the increased distance between parties, differences in currencies, and trading policies. These factors, and more, contribute to the added difficulty in solving global supply chain problems.

Though it may be easier to disregard the international features of a global supply chain when it comes to developing a mathematical model, the solution obtained would not accurately reflect how many industries operate today. A company with physical operations in Canada may require sub-assemblies from China for final products destined for Germany. As each country has its own currency, exchange rates will no doubt play a role in determining the company's net income. Modal choices are also affected, with shipments requiring either transportation by air or sea for intercontinental transactions.

Globalization allows countries to trade more freely with one another, but there are rules that must be followed to ensure that the trade is beneficial to all countries involved. A Canadian company wishing to sell goods purchased from China will be subjected to import duties. This affects the final selling price of the products, increasing them so that they are competitive with domestic goods of comparable quality. Without these tariffs, domestic producers may be at a disadvantage trying to compete with international companies who can offer the goods at discounted prices. Some products, however, are regularly imported by countries if they are not available otherwise. For example, the U.S. is a major importer of Canadian softwood lumber. To foster this relationship and encourage continual trade between these countries and others, certain restrictions on tariffs are relaxed through free trade agreements.

The North American Free Trade Agreement (NAFTA) and the European Union (EU) are examples of international agreements that allow groups of countries to import and export goods with reduced tariffs. As long as certain criteria are met, products can cross borders within these free trade zones (FTZs) at little or no cost. In this way, new supplier markets offering skilled labour and cheaper raw materials can be explored, and imported products can be sold at reasonable prices to a wider consumer base.

Leveraging the benefits of a global supply chain is challenging, requiring a thorough understanding of economic and international factors at play. This is especially true for those supply chains spanning multiple FTZs. In this work, we do not attempt to incorporate *all* of these factors, but rather focus on those which we feel provide a solid foundation for future research. We examine a NAFTA-based company wishing to expand its operations to better serve its customers in the EU. The location of a new manufacturing plant, as well as routes and modes of transportation must be chosen so that profits are maximized. In the following sections, we will provide an overview of recent research on facility location and transportation problems, and further discuss the effects of NAFTA and the EU on international supply chains. A description of the problem at hand, its mathematical formulation, and solution methodology will then be presented, followed by a summary of the results and areas for further research.

Chapter 2

Literature Review

While supply chain decisions vary across industries, they generally fall under one or more of the following categories: facility location, sourcing, production, distribution, and transportation. Bookbinder and Matuk (2009) review a number of articles that feature these problems discussed in a global context. In this thesis, we focus on both facility location and transportation problems for a multinational company.

2.1 Facility Location Models

Whether it be a company in its early stages of development, or an established corporation striving to expand, determining the location of new facilities is a major decision that has effects on downstream operations. The financial and time commitments involved can be quite significant, depending on whether the company is leasing or purchasing the facility. It could take years to develop land and build the structure, or find an established property that suits the corporation's needs. The investment may create added jobs in surrounding communities, further deepening the relationship of the corporation with the local municipality. In addition to this, the benefits (or drawbacks) of a location may not be immediately apparent. While a delivery route can be easily modified upon short notice, facility location problems are strategic decisions that rely upon previous trends and long-term forecasts, and are not conducive to quick and substantial changes.

Locating a plant in a foreign country carries all of these traits with some added uncertainty, such as the reliability of the workforce or fluctuations in exchange and tax rates. Companies may be encouraged to invest in a particular region when those governments offer tax or loan incentives, or if local content rules are in play. These topics will be discussed later in Section 2.3. In a recent review, Melo et al. (2009) discuss the impact that financial factors can have on the design of the network. Those authors note that other decisions, such as the choice of transportation mode or routing of material, should be integrated into facility location models to generate more realistic solutions. We feel that the following selection of articles demonstrates that point, and the growing trend towards comprehensive models.

Robinson and Bookbinder (2007) present a facility location and transportation model for a NAFTA-based company. Given a set of customers, the model determines whether it is cost-effective to use a *maquiladora*, or labour-intensive plant, in Mexico rather than opening a facility in Canada or the U.S. Though the maquiladora is further from the finishing plants, the fixed and variable costs incurred in Mexico are much less than what would be charged elsewhere. The authors assume that the network is not yet established, that is, no facilities are open initially. Because of this, a warm-up period is required to allow time for inventory to be produced, and possibly held, before being shipped out to customers. A similar methodology is used in this work, as our model assumptions are analogous.

The work by Wilhelm et al. (2005) also examines a NAFTA supply chain, placing emphasis on the technical details of the free trade agreement. Constraints reflect local content requirements, bills of materials, and income taxes. The entire supply chain network is modeled, from the location of production facilities and distribution centers, to the modes of transportation by which material will travel between each origin and destination pair. Decision variables include the amount of each item to produce, the number of backorders for end items, and transfer prices. To overcome the non-linearity imposed by the transfer prices, the authors replace the product of two decision variables (i.e. transfer price $\times$ number of units) with one new variable representing revenue. Once the model is solved, the values of revenue and number of units produced can be used to determine the transfer price charged.

The two previous articles focus on the interactions between the three NAFTA countries, though most supply chains these days will span numerous countries, each with their own trading policies. Kouvelis et al. (2004) analyze the effects of tax incentives, government loans, free trade zones, and local content requirements (LCRs) on the design of a global supply chain. With each scenario, the authors show how the network of facilities changes in reaction to the imposed parameter values. An important finding in this research is the effect of the LCR percentage on the location of facilities. While local governments or member countries of a free trade zone intend for LCRs to entice foreign investment, setting the percentage too high could have the opposite effect. Instead of being restricted to use expensive domestic suppliers, a corporation would rather source from a cheaper foreign producer and incur tariffs on the goods it ships to the particular free trade area.

Goetschalckx et al. (2002) show the importance of considering location decisions in their tactical production-distribution model. Benders decomposition is employed to find the optimal network design and transportation plan for a company with seasonal demand. The master problem determines which facilities to use, as well as how much to produce and hold, while the subproblem finds the least costly transportation flows. Though their model pertains to a domestic supply chain, their integration of both location and transportation decisions in one model is consistent with the theme in the present work.

2.2 Transportation Problems

The main modes of transportation we consider are truck, rail, air, and ocean. Each has its own strengths that make it appealing to use under certain circumstances. Cost and time are the most common measures used, but others could include reliability of service or the percentage of damage to inventory by mode. We incorporate the differences in cost and lead time in our model to distinguish each mode from the other.

Transportation by truck is best for short to medium distances and high-valued goods, such as automotive parts. It provides fast service at competitive rates with low reports of damage to products Coyle et al. (2005). Truckload (TL) service requires very little in terms of start-up costs and equipment, as material is shipped door-to-door with no stops or handling of products in between. Less-than-truckload (LTL), however, involves first picking up all material and sorting it at a consolidation center, then driving the long-haul to the next terminal to de-consolidate material before delivery to its final destinations. Even with extra facilities and processing, carriage by truck, whether TL or LTL, allows for lower rates compared to air.

Bulk commodities, such as coal or grains, are best transported by rail. Their value is low compared to manufactured goods, and are less liable to damage on their journey. The large quantities shipped and long distances traveled make rail the most cost-effective choice. For companies with rail sidings, it is also convenient, as material can be received on site. If this is not an option, additional transport by another mode is required to deliver the material to the receiver. Many railroads are offering this intermodal service to appeal to customers, saving them the trouble of coordinating the initial or final leg of the shipment.

While airplanes may be able to travel at higher speeds, they are not ideal for shorter distances due to the strict schedules and policies they impose compared to truck (i.e. arriving at least 3 hours before departure, travel time to and from the airport, etc.). For shipment of high-valued or time-sensitive goods over long distances, air is the mode of choice, providing quicker service than others and with less damage.

Longer lead times make transportation by ocean best for greater distances when demand is steady and travel arrangements can be made in advance. For international shipments, this mode is less costly than air but much slower. Like the convenience of container-on-flat-car (COFC) for rail service, less handling is required when loading or unloading containers from a vessel, though a portion or the journey will require another mode, such as rail or truck, to get from the port to the customer.

Chang (2008) uses Lagrangian relaxation to solve an international intermodal transportation problem, subject to time window constraints. There are two objectives in the proposed model: minimize total costs and minimize travel time. Given the different types of transportation, these objectives can be conflicting. To keep costs low, carriage by ocean is the ideal choice, but this will take significantly longer than shipment by air. To solve the problem, both objectives are combined using a weighting factor that expresses time as an equivalent cost. The weight can be changed depending on the relative importance of each factor. The author finds that when minimizing cost is emphasized, ocean transportation is chosen, while air is preferred when travel time is more important.

For transportation in NAFTA, Bookbinder and Fox (1998) examine routes originating in Canada destined for cities in Mexico. Their analysis considers intermodal routes, using a combination of truck, rail, or ocean. Using a shortest path algorithm, these authors find non-dominated routes providing either the lowest total cost or shortest total time. As the cities in Canada span a greater east-to-west distance than in Mexico, the solution quality is found to be more dependent on the origin city than the destination. Cities near the "center" of Canada, such as Calgary, are able to provide more direct routes with fewer transshipment points than cities on the coast, such as Vancouver. From these routes, Bookbinder and Fox are able to show the ranges of inventory holding costs for which certain routes would outperform another.

Other articles pertaining to transportation policies in the EU and NAFTA are discussed in Subsection 2.3.3. Many more articles are reviewed in Bookbinder and Matuk (2009), but we feel that they examine only one of the two dimensions we are interested in for this work: either modal choices or international transportation. Examples include Jeong et al. (2007) who focus on the rail network in Europe, Groothedde et al. (2005) with their work on hub networks in the Netherlands, and tank repositioning by Erera et al. (2005).

2.3 Free Trade Agreements

Countries enter into free trade agreements (FTAs) for a number of reasons, the main being a reduced cost to trade with one another. For countries that engage in exporting and importing goods frequently, an FTA allows these transactions to occur at a discount in the hopes of encouraging further economic and political ties. A number of agreements currently exist, such as MERCOSUR in South America and ASEAN in southeast Asia, but our attention in this work is focused on NAFTA and the EU.

2.3.1 The North American Free Trade Agreement

The North American Free Trade Agreement (NAFTA) was put into effect on January 1, 1994. The agreement allows the United States, Mexico, and Canada to import goods from one another at reduced or zero tariffs. In doing so, the three countries are able to boost the North American economy by sourcing from domestic suppliers and compete with international corporations. While NAFTA is beneficial for each of its members, it allows Canada and Mexico to compete more fairly with the U.S., whose economy is much stronger than its neighbours (Wolinetz, 2003).

Material must qualify for tariff reductions based on rules of origin. Chapter 4 of the NAFTA (Department of Foreign Affairs and International Trade Canada, 2009) details two methods that can be used to determine the regional content value (RCV) of a product: the net cost method or the transaction value method. In either case, the value of non-originating material must be known. To be eligible for tariff exemption, the RCV must be greater than 60% if the transaction value is used, or 50% for the net cost method. Goods may also be exempted from tariffs if the non-originating material makes up less than 7% of its total cost.

2.3.2 The European Union

Initially established as the European Coal and Steel Community after World War II, the European Union (EU) has evolved from six countries focused on the free trade of coal and steel (and peace after war), to a group of 27 members diverse, yet unified, in social, political, and environmental values. Acting together, the EU allows each of its members to be on a level playing field with the U.S. (Wolinetz, 2003). Most of the expansion in recent years includes eastern countries, such as Romania and the Czech Republic. Like Mexico, these countries provide services at cheaper costs compared to their western counterparts, making them viable locations for labour-intensive production.

While trade within NAFTA is not yet completely free (as it depends on the local content of goods), this is not the case in the EU. Once products from an external market enter the EU, a common tariff is applied, but these goods can then be traded between member countries with no additional tariffs. In this way, the EU is able to reduce trade barriers and move closer towards a single economic market.

The expansion of the EU has promoted trade between member countries by "removing" borders. However, for trade between certain countries, there are still barriers present. Minondo (2007) conducts a study on ten Western EU countries, using their gross domestic product, consumer price indices, and travel distance between pairs of countries to estimate a "tariff" representing the effect of these factors on trade. The author finds that for trade between the Netherlands and Denmark or Finland, the tariff is low, indicating that the countries' borders impose little difficulties on trade. For Austria, however, the tariffs are almost as high as 70% for trade with France, Italy and Spain, even though all countries are EU-member states. The results imply that countries will be more inclined to trade with others when border difficulties are minimized.

2.3.3 Comparing NAFTA and the EU

Because of its additional dimensions, the governance of the EU is much more complex than that of the NAFTA. The U.S., Canada, and Mexico still operate independently of one another on federal matters, while decision-making in the EU is based on a three-tier system made up of a council, parliament, and commission. Wolinetz (2003) suggests that rather than NAFTA, a better comparison to the EU would be Canada itself. The structure of the Canadian political system, with its federal and provincial levels, make it almost synonymous to individual countries operating distinctively, yet each adopting the same governing policies.

Transportation policies differ in NAFTA and the EU, especially for shipments by rail. While both FTZs experienced declines in the proportion of freight traveling by rail in the

1980s, the share of freight by rail in the U.S. has increased since then, but has declined in the EU. Vassallo and Fagan (2007) note certain procedures that may be hindering the EU's efforts of promoting rail to alleviate congested roadways. Since railroads in the EU were originally centered around domestic shipments, there is little compatibility in terms of infrastructure and labour rules between adjacent countries. Some concepts that have increased productivity in the U.S. are not as easily applied in the EU, such as double-stacking rail cars, as there are more tunnels through which the train may pass, each with varying, and possibly, insufficient height. In addition to these concerns, priority is given to passenger trains, which does not allow for efficient freight service.

Nair et al. (2008) also analyze the rail network in Europe, with particular focus on the REORIENT Corridor, spanning from Scandinavia to Greece. This corridor has the potential to shift freight share from truck to rail, but certain factors must first be addressed. Using scenario analysis, these authors confirm that infrastructure improvement is necessary to be able to provide higher levels of service to customers, in addition to relaxing the priority placed on passenger movement on railways.

2.4 Effect of International Factors

2.4.1 Financial Factors

Duties, transfer prices, and corporate tax rates each play a role in the design of a global network. Corporations must investigate the trade-offs between locating near suppliers or customers to save on transportation costs, or capitalizing on the benefits offered by duty- or tax-free zones though they may be further. Feng and Wu (2009) examine a supply chain with the potential to use DCs in international logistics zones that are exempt from duties. They show that it is advantageous to carry out certain manufacturing processes there to save on added costs, though it involves additional transportation between multiple countries. Their sensitivity analysis varies tax parameters and demonstrates that when these values are not imposed, the supply chain remains centralized, with production processes remaining in a single country.

Tax rates do not always remain constant. Governments may sometimes grant tax holidays to entice new investments in their countries, and for an established business, this could hinder sales. As competitors with newer technologies jump at the opportunity to expand their consumer market, older firms may not be able to remain profitable operating at lower costs. In Das and Sengupta (2009), the authors assume that a local manufacturer is faced with competition as well as increased costs for input resources. The manufacturer may outsource some of its work to neighbouring plants so that it can remain a legitimate player in the industry. They develop a strategic model to determine the location and quantity of material to ship to DCs, and the allocation of DCs to customers. With this information, an operational plan then details a production and safety stock policy, along with daily transportation schedules that considers uncertain lead times and demand. Their proposed hierarchical plan is similar to the solution approach employed in this thesis.

Transfer prices can also play a significant role in the maximization of after-tax profit. They act as an internal sales price when "selling" a unit between two subsidiaries of a company. This situation generally arises when an end item is composed of a number of sub-assemblies which must be acquired from different facilities that are part of the same corporation. Increasing the transfer price benefits the selling division by boosting profits, but the buying division will incur added expenses.

Vidal and Goetschalckx (2001) present a local search heuristic that successively solves for transfer prices and transportation cost allocations between two subsidiaries of a multinational firm. By fixing the flow variables, the non-linear profit term is linearized (as in Wilhelm et al., 2005) and a set of transfer prices is found. Using this solution, the model is solved again, this time for the flow values, and the iterative process continues until the solution converges. The authors note that the initial starting point will affect the quality of the solution, due to the non-convexity of the objective function. Perron et al. (2010) present two alternative solution methods to overcome this problem. The first is a meta-heuristic that explores neighbourhoods of solutions both near and far from the incumbent solution, in the hopes of avoiding getting stuck in a local optimum. The second approach is an exact solution using a branch-and-cut algorithm.

The iterative method of solving for transfer prices seems prevalent in current literature.

In Lakhal (2006), the author seeks to maximize operating profits for a network of manufacturing companies that can source material from external suppliers or from divisions within the corporation. The first step in the model is to determine the inbound and outbound flows for each product at every division. Since the author assumes that the divisions operate within the same country, the transfer prices charged for internal transactions will offset one another. Based on the resulting solution, transfer prices can then be determined.

As mentioned earlier, imported goods are subject to duties to ensure that domestic manufacturers can compete fairly with international corporations. However, when these goods are used in a product that will later be exported, companies may be eligible for a refund or a duty drawback. Arntzen et al. (1995) present this concept in their study of Digital Equipment Corporation's international supply chain, though they focus on a single product and do not consider corporate taxes.

Oh and Karimi (2006) extend the previous work by developing a linear programming model for multiple products, taking into account taxes, import duties and duty drawbacks. By comparing two scenarios, one with duty drawbacks and the other without, Oh and Karimi show that companies have the potential to post higher earnings if duty drawbacks are sought. Corporations, however, might not apply for the drawbacks; the process can be extensive. In the U.S. and countries in the EU, bills of materials (BOMs) are needed to define how the imported material is used, along with additional "evidence to substantiate the numbers in the proposed BOM" (Oh and Karimi, 2006).

Investment costs should also be considered in a supply chain model. In the work by Chakravarty (2005), an international corporation must decide how much to invest in a number of plants situated in different countries, subject to a budget constraint. The plants can produce a range of products that will be shipped to various countries where customers exist. The unit cost is composed of the variable production cost and overhead charge, and can be adjusted to recoup the initial investment costs. The overhead charge will vary, depending on the product. Chakravarty finds that when tariffs are considered, the allocation of the overhead is dependent on the other cost components of the product: those with low transportation, production, or tariff rates will be chosen to have a higher overhead, leveling out the total cost for all items.

2.4.2 Rules of Origin

The policies of a free trade agreement do not only affect location decisions, but sourcing strategies as well. Li et al. (2007) examine a global supply chain, where two countries are members of a FTZ but have the option to acquire products from other non-member states. Components that meet the minimum qualifying local content percentage (see Section 2.3) are exempt from tariffs, but are more expensive to procure. Those products that do not qualify for tariff exemption, however, are generally cheaper. Column generation is used to determine the sourcing plan with the lowest total cost. The authors find that costs increase when the minimum qualifying percentage increases, but will plateau after a certain point, when most material is sourced from within the FTZ.

The work in this thesis is based mainly on the articles by Robinson and Bookbinder (2007) and Wilhelm et al. (2005). Important aspects from each article are combined in the model assumptions and formulation, namely the consideration of lead times and modal choices (as in Robinson and Bookbinder), and the bill of materials structure (as in Wilhelm et al.). The determination of transfer prices, as presented by Lakhal (2006), Vidal and Goetschalckx (2001), and Wilhelm et al. , is beyond the scope of this thesis, however, we do examine the sensitivity of the solution when the values of these parameters are changed.

Chapter 3

Problem Statement

Suppose that a NAFTA-based company supplies a product to both the NAFTA and EU markets. The product consists of a number of sub-assemblies that are manufactured at a plant in Monterrey, Mexico. Assembly of the final product takes place in distribution centers (DCs) in Canada, the United States, and various countries in Europe, after which the products are shipped to customers in both Europe and North America.

We investigate a scenario in which the company can no longer keep up with growing demand in both markets and decides to expand its operations in Europe to better serve its customers there. With DCs already established in Western Europe, the company is interested in opening a new manufacturing facility in Eastern Europe to complement the NAFTA facility. The company wishes to determine the location of the new EU manufacturing plant as well as the location of DCs in both regions, along with the routes and modes by which material will be transported so that total net income will be maximized.

Some assumptions are made to limit the scope of the problem, allowing for a more general solution approach. These may be relaxed to suit the needs of a particular company.

1. Only one manufacturing plant is to be chosen for operations in the EU;
2. The NAFTA and EU manufacturing plants can supply DCs in either region. This allows for postponement of production;

3. The DCs can only serve customers in their region;

4. There is no lead time from DCs to customers. We assume that the customer takes ownership of material at the DC.

The potential manufacturing plant locations, DCs, and customers are shown in Figure 3.1, and Table 3.1 lists the city and country names for each facility type.

Companies with analogous network structures include automotive parts suppliers, such as Stoneridge, Inc., which in 2007, captured 10% of the worldwide commercial vehicle interior market (Lazich, 2010). Using that company as a potential candidate for the present work, we base our parameter values on their recent financial reportings, as well as leading competitors in their market segment (e.g. Continental AG, Magna International Inc., TRW Automotive Holdings Corp., and Johnson Controls, Inc.). This is further described in Section 3.2.

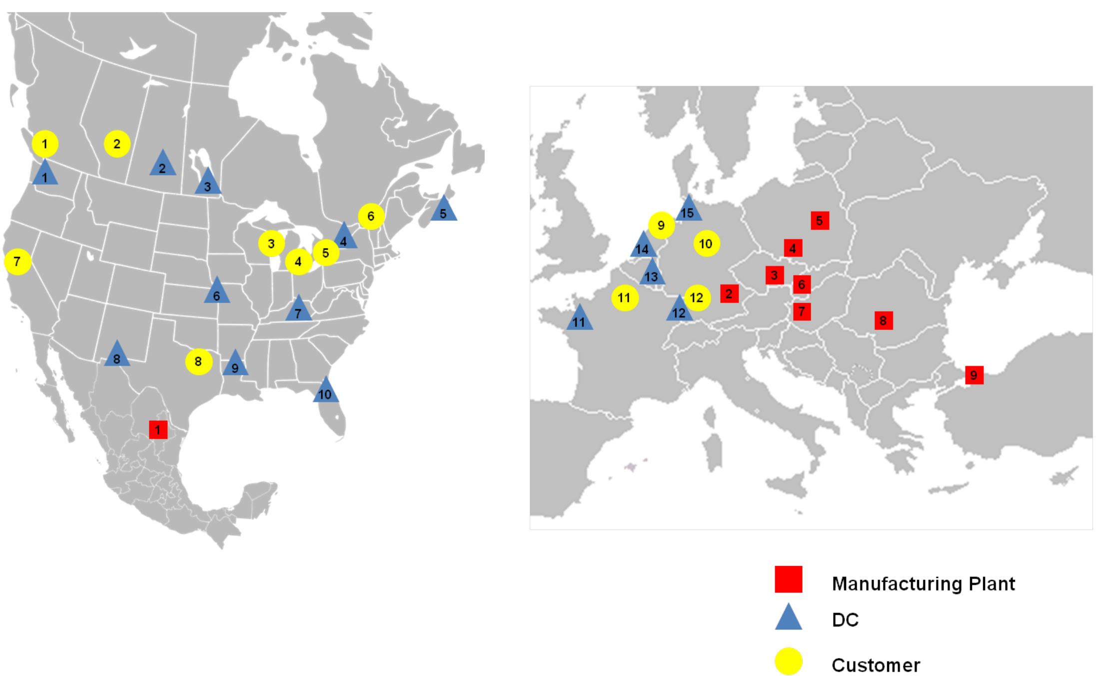


Figure 3.1: Plant, DC, and Customer Locations

	City	Country
1.	Monterrey	Mexico
2.	Regensburg	Germany
3.	Hluk	Czech Republic
4.	Tychy	Poland
5.	Warsaw	Poland
6.	Nitra	Slovakia
7.	Gyor	Hungary
8.	Campulung	Romania
9.	Istanbul	Turkey

(a) Potential Manufacturing Plant Locations

	City	Country
1.	Tacoma	USA
2.	Regina	Canada
3.	Winnipeg	Canada
4.	Oshawa	Canada
5.	Halifax	Canada
6.	Kansas City	USA
7.	Lexington	USA
8.	El Paso	USA
9.	Shreveport	USA
10.	Jacksonville	USA
11.	Guipry	France
12.	Strasbourg	France
13.	Genk	Belgium
14.	Rotterdam	Netherlands
15.	Emden	Germany

(b) Potential DC Locations

	City	Country
1.	Vancouver	Canada
2.	Calgary	Canada
3.	Milwaukee	USA
4.	Detroit	USA
5.	Toronto	Canada
6.	Montreal	Canada
7.	San Francisco	USA
8.	Dallas	USA
9.	Weesp	Netherlands
10.	Hannover	Germany
11.	Cergy	France
12.	Stuttgart	Germany

(c) Customer Locations

Table 3.1: Locations by Facility Type

The company has a number of feasible sites in Eastern Europe from which it can choose to locate the new manufacturing plant. Factors affecting its decision include the costs to operate the facility and to produce and hold the sub-assemblies. The modes of transportation available to ship parts from plants to DCs may also influence the choice of location, along with the transfer prices charged to account for the internal sale of goods and the selling price paid by customers. Since the problem spans multiple time periods, the discount and income tax rates will also impact the overall profit of the company.

3.1 Model Formulation

Two types of decisions are made in this problem. The first is the strategic location of manufacturing plants and DCs, and the second concerns the modal choices for material flows. Each of these decisions relies on a different time scale: a strategic plan focuses on long-term or yearly activities, while an operational plan details more of the day-to-day tasks. Because of this, it is reasonable to approach each problem separately, rather than solve them both using multiple bi-weekly time horizons. In this way, location decisions are determined once only in the strategic model, while the operational model can be re-solved as needed, to account for any revisions in production and distribution activities.

There are only slight variations between each formulation. In the strategic model (SM), each time period t represents one month and a solution is found for a time horizon of one year ($T = 12$). Lead times are not considered, as the time periods are long enough that we can assume material will arrive within the month-long period. The operational model (OM) uses daily periods, with $t = 1$ day. As product flows and costs are greatly influenced by the lead times associated with each transportation mode, lead times must be present in this formulation.

We express the model as a mixed integer linear program whose objective is to maximize the after-tax profit of the company. A detailed list of indices, sets, parameters and decision variables can be found in Section 3.1.1. As both SM and OM are quite similar, the former model is presented below, with the differences in OM discussed in Section 3.1.3.

3.1.1 Notation

Indices and Sets

$\theta \in \Theta$	set of regions, where $\theta = 1$ represents the EU and $\theta = 2$ is NAFTA
$c \in \theta$	set of countries in θ
$i \in I_c$	set of potential manufacturing plant locations in c
$j \in J_c$	set of potential DC locations in c
$k \in K_c$	set of customers in c
$m \in M$	set of transportation modes
$s \in S$	set of sub-assemblies
$1 \leq t \leq T$	time horizon

Parameters

A_s	=	number of sub-assemblies of type s required in one unit of final product
a_{ijm}	=	cost of transporting one unit from plant i to DC j by mode m
b_{jkm}	=	cost of distributing a unit of final product from DC j to customer k by mode m
$d_k(t)$	=	demand of customer k in period t
f_i	=	fixed cost per period of operating plant i
$\tilde{f}_j$	=	fixed cost per period of operating DC j
h_{is}	=	carrying cost per unit of sub-assembly s at plant i, applied to the stock carried over from the previous period
$\tilde{h}_{js}$	=	carrying cost per unit of sub-assembly s at DC j, applied to the stock carried over from the previous period
$\tilde{h}_j$	=	carrying cost per unit of final product at DC j, applied to the stock carried over from the previous period
l_{ijm}	=	lead time from plant i to DC j by mode m
n_{is}	=	maximum inventory of sub-assembly s at plant i
$\tilde{n}_{js}$	=	maximum inventory of sub-assembly s at DC j

$\tilde{n}_j$	=	maximum inventory of final product at DC j
p_s	=	pipeline inventory cost of one unit of sub-assembly s per unit
q_{is}	=	unit variable cost of producing sub-assembly s at plant i
$\tilde{q}_j$	=	unit variable cost of assembling final product at DC j
r_c	=	discount rate in country c
w_{is}	=	maximum throughput of sub-assembly s at plant i
$\tilde{w}_j$	=	maximum throughput of DC j
TAX_c	=	corporate tax rate in country c
τ_{ijs}	=	transfer price charged by plant i for completed sub-assembly s shipped to DC j
ρ_k	=	selling price of final product to customer k

Decision Variables

$\lambda_{is}(t)$	=	number of units of sub-assembly s produced by plant i in period t
$X_{ijms}(t)$	=	number of units of sub-assembly s moved from plant i using mode m arriving at DC j in period t
$Y_{jkm}(t)$	=	number of units of final product moved from DC j using mode m arriving at customer group k in period t
$u_{js}(t)$	=	number of units of final product that can be made from sub-assembly s received at DC j in period t
$\bar{u}_j(t)$	=	maximum number of units of final product that can be assembled at DC j in period t
$N_{is}(t)$	=	inventory of sub-assembly s at plant i, carried from $(t-1)$ to t
$\tilde{N}_{js}(t)$	=	inventory of sub-assembly s at DC j, carried from $(t-1)$ to t
$\tilde{N}_j(t)$	=	inventory of final product at DC j, carried from $(t-1)$ to t
$S_{ij}(t)$	=	1, if plant i serves DC j in period t; 0 otherwise
$Z_{jk}(t)$	=	1, if DC j serves customer k in period t; 0 otherwise
V_i	=	1, if plant i is open; 0 otherwise
$\tilde{V}_j$	=	1, if DC j is open; 0 otherwise

3.1.2 Strategic Model

The objective function captures the net income before tax (NIBT) for each country in period t and is calculated as follows:

$$
\begin{aligned}
\pi_{ct} =& \\
&\sum_{i \in I_c} \left(\sum_{j,m,s} \tau_{ijs} X_{ijms}(t) - \left[\sum_{s} \Big(q_{is}\lambda_{is}(t) + h_{is}N_{is}(t) + \sum_{j,m} \big(a_{ijm} + p_s l_{ijm}\big) X_{ijms}(t) \Big) + f_i V_i \right] \right) \\
&+ \sum_{j \in J_c} \left(\sum_{k,m} \rho_k Y_{jkm}(t) - \left[\sum_{i,m,s} \tau_{ijs} X_{ijms}(t) + \tilde{q}_j \bar{u}_j(t) + \sum_{s} \tilde{h}_{js} \tilde{N}_{js}(t) + \tilde{h}_j \tilde{N}_j(t) \right.\right. \\
&\qquad \left.\left. + \sum_{k,m} b_{jkm} Y_{jkm}(t) + \tilde{f}_j \tilde{V}_j \right] \right)
\end{aligned} \tag{3.1}
$$

We note that cost and profit parameters are converted to U.S. dollars explicitly using published exchange rates that are assumed to be constant.

The first set of summations calculates the NIBT for all manufacturing plants i in country c. The first term in this summation group denotes the revenue generated from "selling" the sub-assemblies to DCs. We subtract from this the cost of production, cost of holding inventory, transportation and pipeline inventory costs, and the fixed cost of operating plant i.

Similarly, for DCs j in country c, we subtract from the final product revenue the costs of assembly, holding inventories of s and final products, distribution to customers, and the fixed cost of operating DC j.

Our objective then is to maximize after-tax profits, summed over each country and discounted over all time periods:

$$
\max \sum_{c,t} \frac{\pi_{ct}(1 - TAX_c)}{(1 + r_c)^t} \tag{3.2}
$$

The constraints are presented in a way that logically follows the flow of manufacturing and assembly operations in a supply chain. We begin at the manufacturing facilities:

$$\sum_{i \in I_1} V_i = 1 \tag{3.3}$$

$$\lambda_{is}(t) - w_{is} V_i \leq 0 \qquad \forall i, s, t \tag{3.4}$$

$$N_{is}(t) - n_{is} \leq 0 \qquad \forall i, s, t \tag{3.5}$$

$$S_{ij}(t) - \tilde{V}_j \leq 0 \qquad \forall i, j, t \tag{3.6}$$

$$S_{ij}(t) - V_i \leq 0 \qquad \forall i, j, t \tag{3.7}$$

$$\sum_{m} X_{ijms}(t) - w_{is} S_{ij}(t) \leq 0 \qquad \forall i, j, s, t \tag{3.8}$$

$$\sum_{j,m,s} X_{ijms}(t) - \sum_{s} w_{is} V_i \leq 0 \qquad \forall i, t \tag{3.9}$$

$$N_{is}(t) + \lambda_{is}(t) - \sum_{j,m} X_{ijms}(t) - N_{is}(t+1) = 0 \qquad \forall i, s, t \tag{3.10}$$

$$X_{ijms}(t) - \sum_{j,m} \sum_{\hat{t}=1}^{t-1} X_{ijms}(\hat{t}\,) - \sum_{\hat{t}=1}^{t} \lambda_{is}(\hat{t}\,) - N_{is}(t) \leq 0 \qquad \forall i, s, t \tag{3.11}$$

Equation 3.3 allows only one plant to be chosen in the EU region. Constraints 3.4 ensure that the number of sub-assemblies produced is less than the maximum throughput of plant i, and that they are produced only if plant i is open. Inventory restrictions for sub-assembly s are reflected in constraints 3.5.

In order to serve a DC, a link $S_{ij}(t)$ must exist between both plant i and DC j, and the facilities must both be open, as shown in constraints 3.6 and 3.7. In addition to this, sub-assemblies can only flow from plant i to DC j on existing links 3.8 and from plants that are open 3.9. Flow balance is conserved in equation 3.10, while constraint 3.11 states that before material can be shipped, it must currently be in stock or have been manufactured previously. Without this constraint, material arrives at DCs before it is produced (i.e. $X_{ijms}(t) > 0$ when $\lambda_{is}(t) = 0$), which should not occur.

Constraints pertaining to DC operations and flow are presented below:

$$A_s u_{js}(t) - \left(\sum_{i,m} X_{ijms}(t) + \tilde{N}_{js}(t) \right) = 0 \qquad \forall j, s, t \tag{3.12}$$

$$\bar{u}_j(t) - u_{js}(t) \leq 0 \qquad \forall j, s, t \tag{3.13}$$

$$\bar{u}_j(t) - \tilde{w}_j \tilde{V}_j \leq 0 \qquad \forall j, t \tag{3.14}$$

$$\tilde{N}_{js}(t) - \tilde{n}_{js} \leq 0 \qquad \forall j, s, t \tag{3.15}$$

$$\tilde{N}_j(t) - \tilde{n}_j \leq 0 \qquad \forall j, t \tag{3.16}$$

$$Z_{jk}(t) - \tilde{V}_j \leq 0 \qquad \forall j \in J_\theta, k \in K_\theta, t, \theta \tag{3.17}$$

$$\sum_m Y_{jkm}(t) - \tilde{w}_j Z_{jk}(t) \leq 0 \qquad \forall j \in J_\theta, k \in K_\theta, t, \theta \tag{3.18}$$

$$\sum_{j \in J_\theta} \sum_m Y_{jkm}(t) - d_k(t) = 0 \qquad \forall k \in K_\theta, t, \theta \tag{3.19}$$

$$\tilde{N}_{js}(t) + \sum_{i,m} X_{ijms}(t) - A_s \bar{u}_j(t) - \tilde{N}_{js}(t+1) = 0 \qquad \forall j, s, t \tag{3.20}$$

$$\tilde{N}_j(t) + \bar{u}_j(t) - \sum_{k \in K_\theta} \sum_m Y_{jkm}(t) - \tilde{N}_j(t+1) = 0 \qquad \forall j \in J_\theta, t, \theta \tag{3.21}$$

$$\lambda_{is}(t), X_{ijms}(t), Y_{jkm}(t), u_{js}(t), \bar{u}_j(t), N_{is}(t), \tilde{N}_{js}(t), \tilde{N}_j(t) \in \mathbb{R}^+ \tag{3.22}$$

$$S_{ij}(t), Z_{jk}(t), V_i, \tilde{V}_j \in \{0, 1\} \tag{3.23}$$

The bill of materials is reflected in constraints 3.12 to 3.14. Equation 3.12 transforms the number of sub-assemblies s at DC j into an equivalent number of final products, assuming that all other sub-assemblies are available. Using that information, the maximum number of final products that can be assembled at DC j in period t is expressed in constraint 3.13. The final constraint in this group ensures that the number of final products assembled is less than the maximum throughput of facility j and that assembly only occurs at a DC that is open.

If sub-assembly s is received at DC j, but is not assembled into a final product, it can be held until a later period, as denoted by $\tilde{N}_{js}(t)$. If sub-assemblies are assembled into final products but are not distributed to customer k, they are also held until a later period as $\tilde{N}_j(t)$. Constraints 3.15 and 3.16 ensure that maximum allowable inventory levels at DC j are not violated. In this model, we assume that customer demand must be satisfied, as shown in equation 3.19. Note that the actual number of units of final product shipped to customer k is denoted by $Y_{jkm}(t)$. Flow balance at plant i and DC j for both sub-assemblies and final products is reflected in equations 3.10, 3.20, and 3.21.

Finally, we define flow variables over the set of non-negative real numbers, while other variables take on binary values. The initial inventory values, $N_{is}(1), \tilde{N}_{js}(1)$, and $\tilde{N}_j(1)$, are all set to zero as we begin with no stock on hand.

We note that for equations 3.17 to 3.19, two constraints could have been used to accomplish the same goal:

$$\sum_m Y_{jkm}(t) - \tilde{w}_j \tilde{V}_j \leq 0 \qquad \forall j \in J_\theta, k \in K_\theta, t, \theta \tag{3.18$'$}$$

$$\sum_{j \in J_\theta} \sum_m Y_{jkm}(t) Z_{jk}(t) - d_k(t) = 0 \qquad \forall k \in K_\theta, t \tag{3.19$'$}$$

This formulation, however, would produce a non-linear model that would complicate the solution method. By disaggregating the constraints, we are able to solve the model as a mixed integer linear program with GAMS/CPLEX.

3.1.3 Operational Model

Aside from the difference in time scale, OM differs from SM in only two constraints, namely 3.8 and 3.10. At the operational level, the lead times from plant to DC will affect the choice of transportation mode. To reflect this characteristic, those constraints are modified as follows:

$$\sum_m X_{ijms}(t + l_{ijm}) - w_{is} S_{ij}(t) \leq 0 \qquad \forall i, j, s, t \tag{3.8$'$}$$

$$N_{is}(t) + \lambda_{is}(t) - \sum_{j,m} X_{ijms}(t + l_{ijm}) - N_{is}(t+1) = 0 \qquad \forall i, s, t \tag{3.10$'$}$$

Using the solution obtained from SM regarding manufacturing and DC locations, V_i and $\tilde{V}_j$ are now fixed, eliminating those variables and certain decisions for $S_{ij}(t)$ and $Z_{jk}(t)$. DC allocation to customers from SM are also used in OM. These simplifications impact constraints 3.4, 3.6 to 3.9, 3.14, 3.17, and 3.18.

The choice of mode found in SM is not enforced in the operational model due to differences in the time periods used. Since lead times are not considered in SM, the cheapest mode will be chosen there, regardless of the time required to ship the material.

3.2 Data Collection

To determine potential locations for plants, DCs, and customers, we look at competing companies that already have a strong European presence, as well as a supplier or customer base in the NAFTA regions. Knowing where these companies operate, we can reasonably assume that any of these cities will be a viable choice with the necessary resources to support a new manufacturing facility. Resources may include local suppliers, skilled labour, and access to transportation.

The parameter values are derived from financial statements of these competitors, and we feel that they provide a good basis from which to form an initial case for the problem. Using the reported number of units sold by Magna (2009) and the market shares of Continental and Stoneridge (Lazich, p.517), we can estimate the annual customer demand. Selling prices and production costs are based on the net sales and cost of goods sold reported in the financial statements of Stoneridge (2009).

Since transfer prices are intended for internal accounting purposes, the selling price charged to external customers can act as an upper bound on these values. In the base case model, the unit holding costs for sub-assemblies at the manufacturing plants and DCs are initially set to 15% of production costs per unit per year. For final products, we set unit holding costs equal to 25% of the assembly costs per unit per year. Unit pipeline costs are set at $1 per hundredweight, based on data from Robinson and Bookbinder (2007), with a pallet of parts weighing 1000 lbs and containing 500 units.

Most transportation costs and lead times for our origin-destination (O-D) pairs were obtained from an online freight calculator Global Shipping Costs Inc. (2009) and from leading carriers, such as CN Rail (nd) and Maersk (nd), through their online quotation systems. For those O-D pairs that did not produce a quote, their costs and lead times were estimated from the available data. Using a framework similar to that of Bookbinder and Fox (1998), we solved for the fixed and variable costs by solving two equations with two unknowns, based on the distances between nodes.

Overseas routes will, by default, need to use ocean or air carriers for the long-haul portion of their journey, and will generally involve drayage between the port and customer locations by truck or rail once on land. Because of this, the costs and lead times when the modal choice is air or ocean will inherently include the drayage cost and travel time.

The income tax rates are based on rates reported by Canada Revenue Agency, Internal Revenue Service, and European Commission, while discount factors will be linked to the prime lending rates of the countries obtained from Eurostat, Bank of Canada, Banco de México, and the Federal Reserve. (Income tax rates for Mexico are estimated using the U.S. and Canadian tax rates.)

3.3 Solution Methodology

SM is solved first, using $T = 12$ months and parameters reflecting monthly income and tax rates, demand, and costs. The solution provides values for V_i and $\tilde{V}_j$ to use as input for OM.

For OM, lead times are present and affect our selection for the scaling of t. Transportation between an O-D pair can take anywhere from 1 to 30 days, depending on the choice of mode. Due to the wide range in lead times, the smallest logical option for t is 1 day, as it best distinguishes the speed of each mode. For example, if t were one week, the differences between air and truck would be reduced to their costs only, lessening the impact of the modal choice in our model. Since the ocean lead times can be quite long, we set the upper bound on l_{ijm} to be 20 days, i.e. any actual ocean lead time that is greater than 20 will be rounded down. We feel that this assumption still differentiates each mode while allowing us to examine shorter time horizons.

In order to obtain a realistic solution, we must allow the model to "warm up" for a number of periods, where demand is equal to zero. Without this, the model does not have enough time to produce, hold, and send shipments while adhering to the imposed lead times. The warm-up period is set to 20 days; in this way, all modes of transportation are given a fair chance to be used for shipments between origins and destinations. If the warm-up period were shorter, modes with longer lead times may not be considered at all, as shipments will not make it to their destinations in time.

As mentioned earlier, OM now has a reduced number of binary variables, allowing us to use a longer time horizon than if we were to solve the problem in one step. We use $T = 60$ days to determine a two-month operational plan for the company, detailing how much inventory to hold at each plant and DC, when to ship materials, and which plants (DCs) serve which DCs (customers). The time horizon is limited to 60 days as updated forecasts may be generated every week or so. In practice, importance would be placed on the earlier weeks of the operational plan, as demand is more likely to remain firm.

GAMS/CPLEX is used to program and solve the MIP model. We note that flow variables $(X_{ijms}(t), Y_{jkm}(t), N_{is}(t), \tilde{N}_{js}(t), \tilde{N}_j(t))$ are not restricted to integer values, as fractional quantities of material at such high volumes will not hinder results significantly. This feature allows for both SM and OM to be solved relatively quickly (in less than five minutes), as there are fewer integer variables, and for OM, fewer binary variables.

Chapter 4

Numerical Results

In this chapter, we begin by assuming that each location has identical parameter values except for demand, transportation costs and lead times, and allow the models to determine the best plant location and transportation plan based solely on those differences. In each subsequent case, one parameter in the model is changed to observe its effect on the network of facilities and modal choices.

For all cases, we assume that each plant can produce twice the total required demand in any period, to accommodate orders that may be produced in advance to take advantage of slower shipping times (Eq. 4.1). We also assume that each DC can serve at most four customers (Eq. 4.2). Since a plant (DC) may not ship products in every period, it is reasonable to assume that the plant (DC) should be able to hold production (assembly) from yesterday and today. For this reason, we set the maximum inventory levels as twice the amount the plant (DC) is capable of producing (assembling) in a single period.

$$w_{is} = 2 \max_{t} \sum_{k} d_k(t) \qquad \forall i, s \tag{4.1}$$

$$\tilde{w}_j = 4 \max_{k,t} d_k(t) \qquad \forall j \tag{4.2}$$

Demand for each customer is based on the city's population, relative to a reference customer which we have chosen as Vancouver, as its population is closest to the average

City	Scaling Factor	Monthly Demand $1 \leq t \leq 12$	Daily Demand $21 \leq t \leq 80$
Vancouver	1.00	12 000	380
Calgary	0.51	6 108	194
Milwaukee	0.82	9 852	312
Detroit	2.52	30 216	957
Toronto	2.42	28 992	919
Montreal	1.72	20 616	653
San Francisco	1.99	23 844	756
Dallas	3.06	36 732	1 164
Weesp	0.01	97	4
Hannover	0.25	2 952	94
Cergy	0.03	324	11
Stuttgart	0.28	3 396	108

Table 4.1: Scaling Factors and Base Case Demand

and median over all customer populations in this study. The reference demand is set to 12 000 units, with all other demands scaled according to the factors listed in Table 4.1.

Other parameter values for the base case can be found in Appendix A. We remind the reader that the location of the NAFTA plant in Monterrey is assumed to be fixed and that a list and map of locations can be found in Chapter 3.

4.1 Base Case

Regensburg, Germany is chosen by the model as the EU manufacturing plant, due to its shorter lead times and cheaper transportation costs. Only four DCs are opened: Emden, Germany and Kansas City, Shreveport and El Paso, each in the United States. Emden serves all EU customers (recall that we assume DCs can serve only customers in their own FTZ), while some customers in the U.S. are served by more than one DC. Toronto, Montreal, and Milwaukee are served by both Kansas City and Shreveport, and Dallas is served by Shreveport and El Paso. The remaining customers receive shipments from only one DC: Vancouver and Detroit from Kansas City, and Calgary and San Francisco from El Paso (see Figure 4.1).

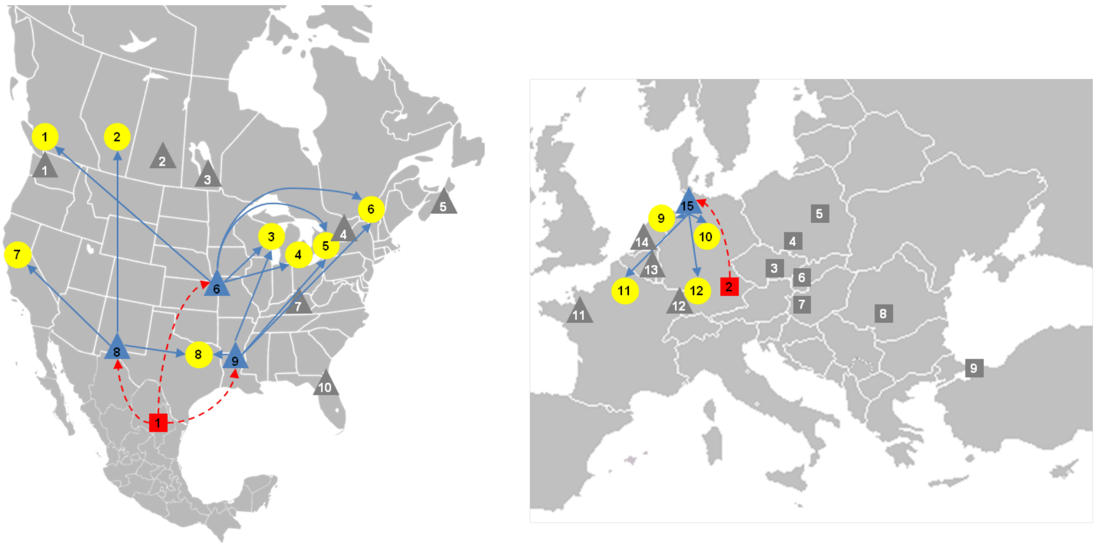


Figure 4.1: Network Configuration: Base Case

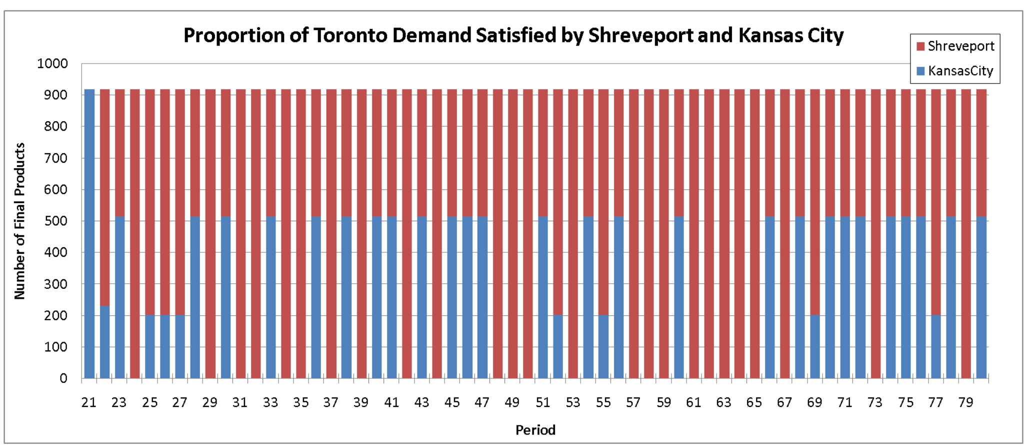


Figure 4.2: Toronto Demand

The allocation of multiple DCs to certain customers introduces patterns by which demand is satisfied. For Toronto and Montreal, they are at times served by Kansas City, Shreveport, or both (Figures 4.2 and 4.3). For example, in period 21, Kansas City supplies Toronto's demand of 919 units; in period 22, Kansas City ships 231 units and Shreveport 688; in period 23, Kansas City now supplies 515 units with Shreveport shipping the remaining quantity; and in period 24 Shreveport supplies all 919 units.

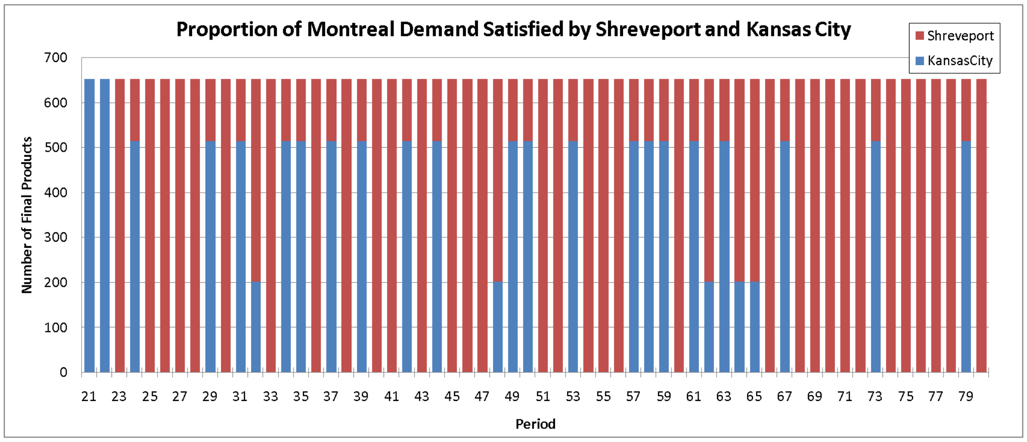


Figure 4.3: Montreal Demand

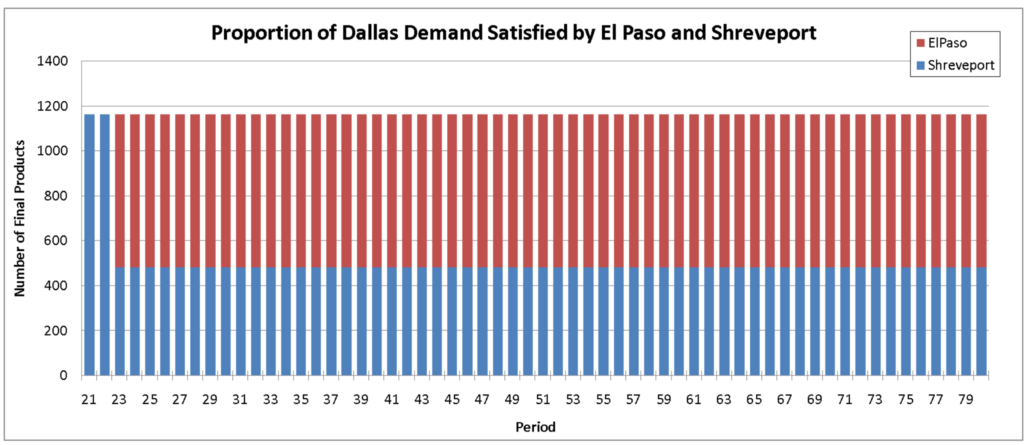


Figure 4.4: Dallas Demand

A more regular pattern is seen for Dallas, which is served by El Paso and Shreveport. In earlier periods ($t = 21, 22$), Dallas is served by Shreveport alone, but after that, the demand is split with Shreveport supplying 483 units and El Paso 681 for the remainder of the planning horizon (Figure 4.4). In contrast to Dallas, Toronto, and Montreal, the Milwaukee customer is fully served in a given period by either Shreveport or Kansas City, but never both (Figure 4.5).

Viewing demand from the DC's perspective, we see that Kansas City supplies Detroit

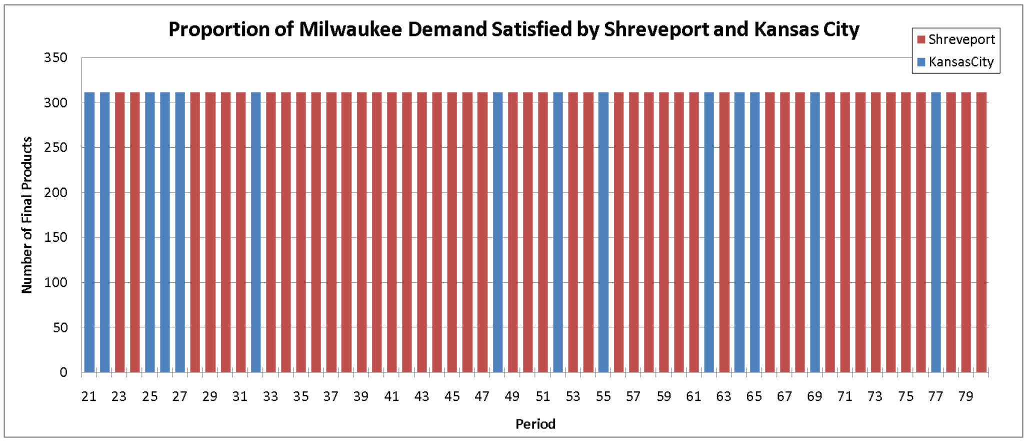


Figure 4.5: Milwaukee Demand

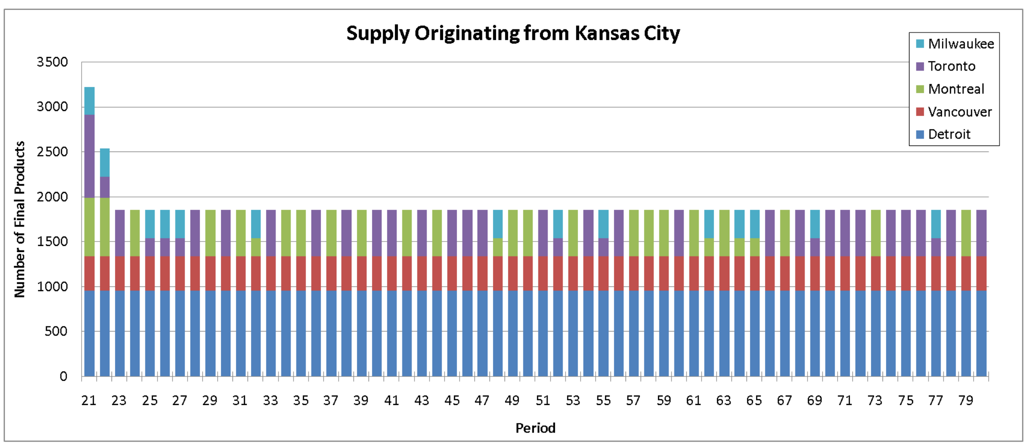


Figure 4.6: Kansas City Supply

with 957 units and Vancouver with 380 units each period, but the amounts shipped to Montreal, Toronto, and Milwaukee vary each period with no discernible pattern (Figure 4.6). A similar situation exists with Shreveport, where Dallas and Milwaukee are sent 483 and 312 units, respectively, in most periods, with varying quantities supplied to Toronto and Montreal through the planning horizon (Figure 4.7). The total shipped from both DCs is never more than 1852 units, the maximum throughput of each DC ($\tilde{w}_j$), except in earlier periods, when inventory has been stored from production during the warm-up interval. El Paso, however, serves its customers the same amount in each period: Calgary

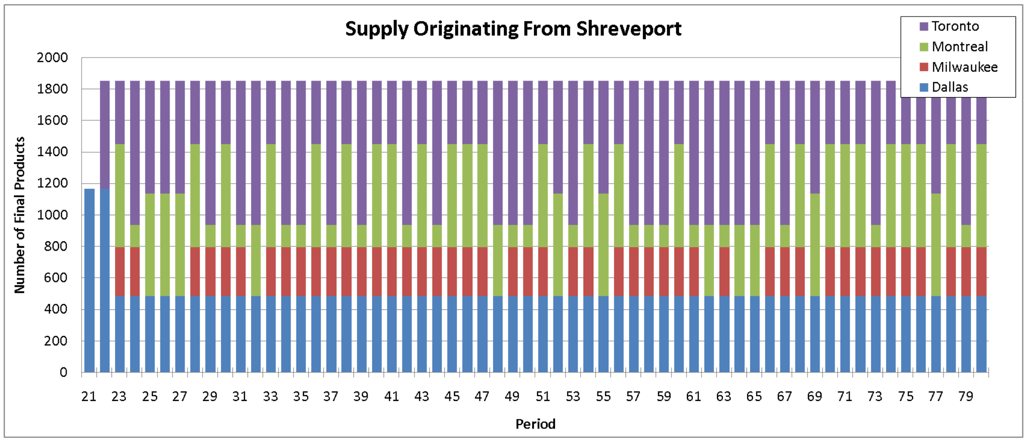


Figure 4.7: Shreveport Supply

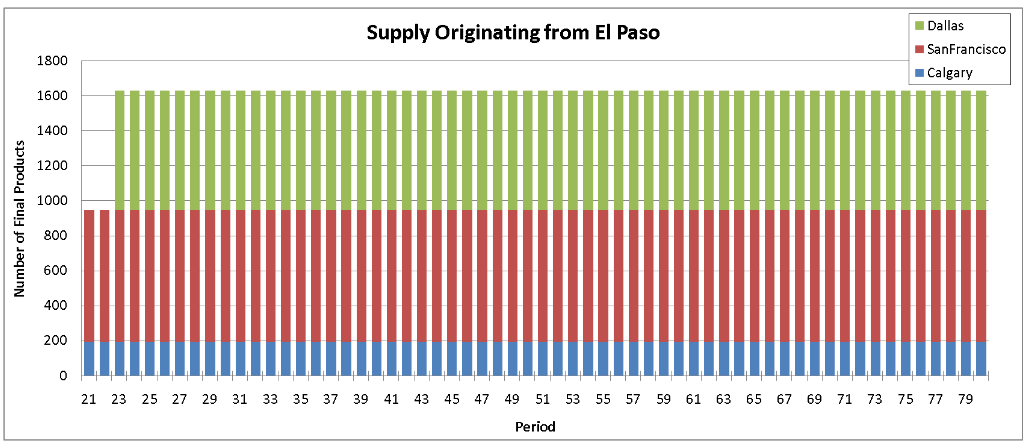


Figure 4.8: El Paso Supply

with 194 units, San Francisco with 756, and Vancouver, and Dallas with 681 (Figure 4.8).

Since there are no inter-continental transactions, the preferred mode of choice is rail for all links as it is cheapest. Production begins in period 15 of the warm-up phase to allow for enough time to build up inventory and then ship products in period 19 from Monterrey. Regensburg can afford to wait to begin production until period 20 (the last period in the warm-up), as it requires less lead time to reach the EU DCs. Final products are held at Kansas City during periods 20 through 22 only.

4.2 Case 1: Western versus Eastern Europe

In Section 2.3.2, we discussed the easterly expansion of the EU, noting that like Mexico, many of the newly acceded Eastern European countries offer lower labour rates than their Western counterparts. In this case, we reflect that characteristic by increasing the fixed and variable costs of the Regensburg plant. The goal is to determine by how much these costs need to increase until a change in plant location occurs.

An increase in costs as small as 0.24% is enough for the model to choose Nitra, Slovakia as the manufacturing plant rather than Regensburg. All other location decisions remain the same as in the base case. Other choices for the manufacturing plant could have been Tychy, Poland or Hluk, Czech Republic, as they each have the same lead time by rail to Emden as Nitra does, and identical transportation costs, which are the lowest after Regensburg.

4.3 Case 2: Varying Transfer Prices

We examine the effect of varying transfer prices between EU (NAFTA) plants and NAFTA (EU) DCs. A decrease in prices will lower the profits of the plant but also lessen the expenses of the DC (if these links are used), while an increase will boost plant profits as well as DC expenses.

When the transfer price is allowed to vary (either positively or negatively), we do not see a change in the resulting network because income tax and discount rates are equal for all countries. The profit earned by the plants is offset by the expense incurred by the DCs when calculating net income. We expect this to change when both transfer prices *and* income tax are varied simultaneously.

4.4 Case 3: Varying Income Tax Rates

We try four scenarios for Case 3. In Case 3(a), we increase the tax rate in Germany to determine at what point the network will change. For Case 3(b) and 3(c), we assume that Romania's and the Czech Republic's tax rates are lower and more attractive to foreign investors. Finally, in Case 3(d), we use the actual income tax rates based on data from the Internal Revenue Service (2010), the European Commission (2009), and the Canada Revenue Agency (2010).

4.4.1 Case 3(a): Increasing TAX for Germany

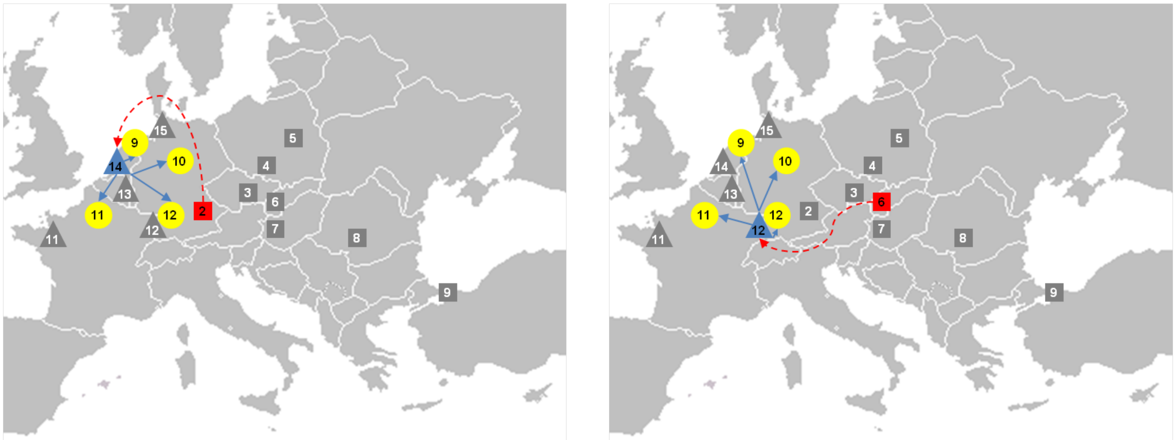
There are two points at which the base case network begins to change. When Germany's tax rate is increased from 25% to 25.59%, the EU DC shifts from Emden to Rotterdam (Figure 4.9(i)). A further increase above 28.34% removes the company's presence from Germany, as Nitra now houses the manufacturing plant and serves a DC in Strasbourg, France (4.9(ii)).

4.4.2 Case 3(b): Decreasing TAX for Romania

Large decreases in Romania's tax rates are required to entice a change from the base case network. Once $TAX_{Romania} \leq 0.94\%$, Campulung becomes the most cost effective manufacturing location, along with Rotterdam for the EU DC. The network in NAFTA remains the same as the base case (Figure 4.10).

4.4.3 Case 3(c): Decreasing TAX for the Czech Republic

Smaller decreases than in Romania are needed before a manufacturing plant is built in the Czech Republic. Lowering taxes below roughly 16.19% will place the facility there, keeping the EU DC in Emden, and the network in NAFTA unchanged (Figure 4.11).



(i) $25.59\% \leq TAX_{Germany} \leq 28.34\%$ (ii) $TAX_{Germany} > 28.34$

Figure 4.9: Network Configuration: Case 3(a) - Varying Germany's Tax Rates

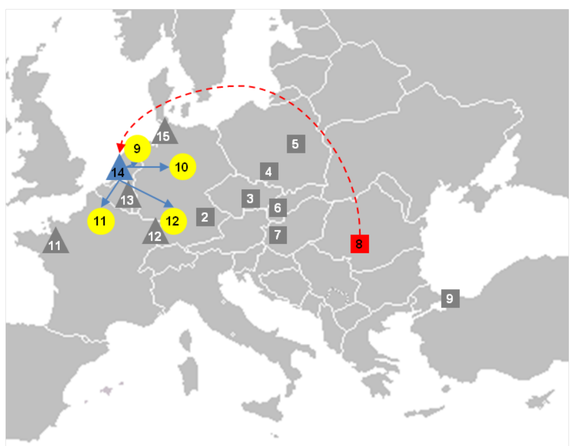


Figure 4.10: Network Configuration: Case 3(b) - $TAX_{Romania} \leq 0.94\%$

4.4.4 Case 3(d): Using Actual Income Tax Rates

When actual income tax rates are used, only the EU network is affected. The plant is now erected in Tychy and the DC is in Rotterdam (Figure 4.12). The tax rates in each of these countries (Poland and the Netherlands, respectively) are lower than in Germany.

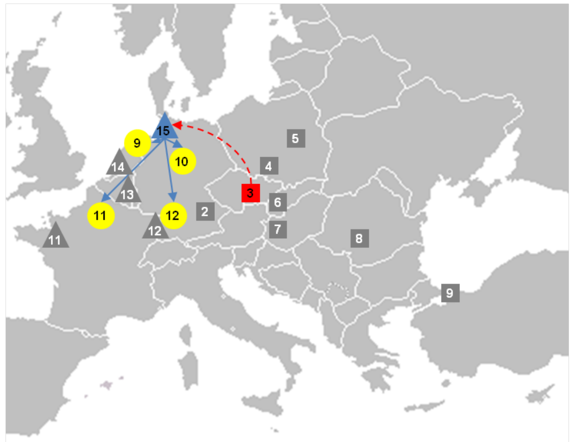


Figure 4.11: Network Configuration: Case 3(c) - $TAX_{CzechRepublic} \leq 16.19\%$

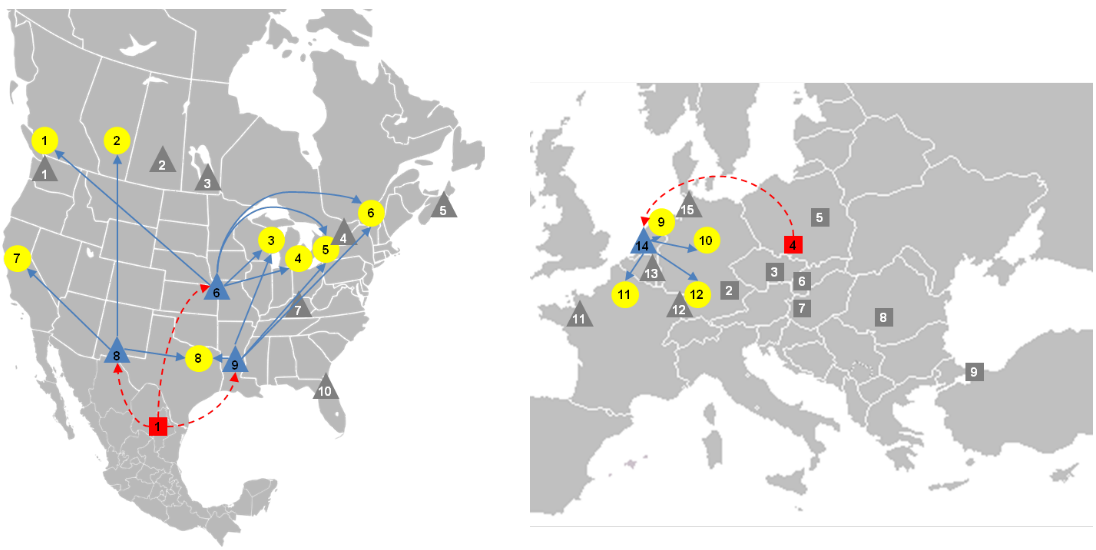


Figure 4.12: Network Configuration: Case 3(d) - Actual Tax Rates

4.5 Case 4: Varying DC Costs

We examine the effect of fixed and variable costs at the distribution centers in certain countries. Using the base case results, we try to determine by how much fixed and variable costs ($\tilde{f}_j$ and $\tilde{q}_j$) need to vary with respect to the other countries before changes in the network appear.

4.5.1 Case 4(a): Increasing Emden's Costs

As in Case 3, small changes in costs will shift certain operations out of Germany. In this scenario, when Emden's fixed and variables costs are increased by 0.27%, Rotterdam now becomes the best EU DC option (Figure 4.13).

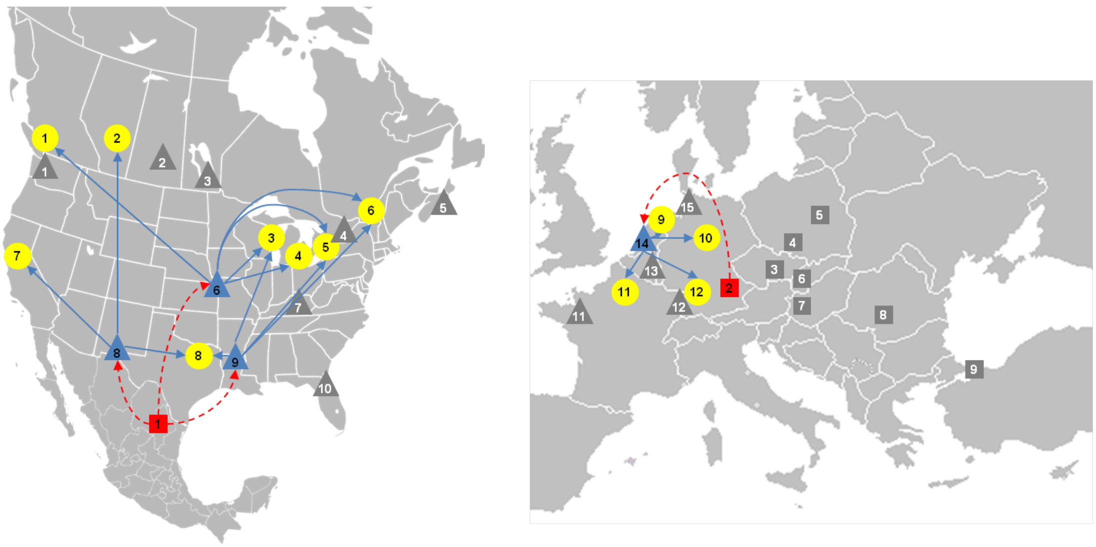


Figure 4.13: Network Configuration: Case 4(a) - Increasing Emden's Costs

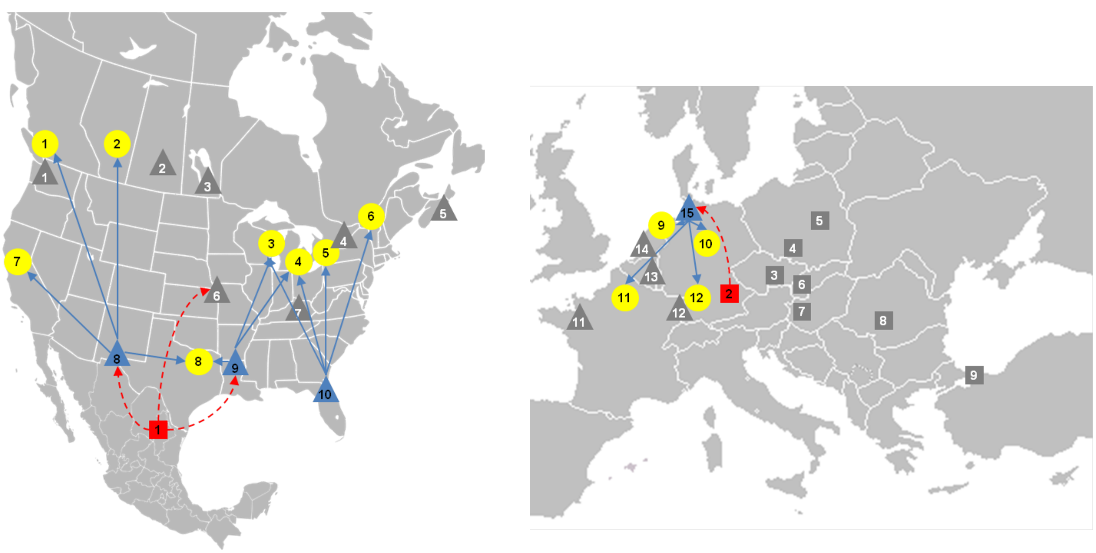


Figure 4.14: Network Configuration: Case 4(b) - Increasing Kansas City's Costs

4.5.2 Case 4(b): Increasing Kansas City's Costs

Slightly higher price increases are required before Kansas City is no longer one of the best NAFTA DC locations. A 1.26% increase will have the model prefer Jacksonville over Kansas City, and a re-allocation of DCs to customers occurs (Figure 4.14). Shreveport now serves Detroit, Milwaukee, and Dallas; El Paso serves Dallas, Calgary, Vancouver, and San Francisco; and Jacksonville is allocated to cities in the northeast - Detroit, Milwaukee, Toronto, and Montreal.

Production begins at $t = 16$ rather than $t = 15$, with final product inventory held at Shreveport in $t = 21$ and 22 (817 and 236 units, respectively), and in El Paso from $t =$ 23 to 25 (177, 118, and 59 units, respectively). The distribution pattern also changes: Shreveport either fully serves Detroit, or supplies 898 units with the remaining 59 units shipped from Jacksonville (Figure 4.15). The same situation arises for Milwaukee, with Shreveport supplying either all the demand, or only 253 units with Jacksonville supplying the remaining 59 units (Figure 4.16). In Dallas, and with the exception of the first few periods in the planning horizon, the proportion of demand supplied by each DC remains constant: El Paso and Shreveport ship 522 and 642 units of final product, respectively (Figure 4.17).

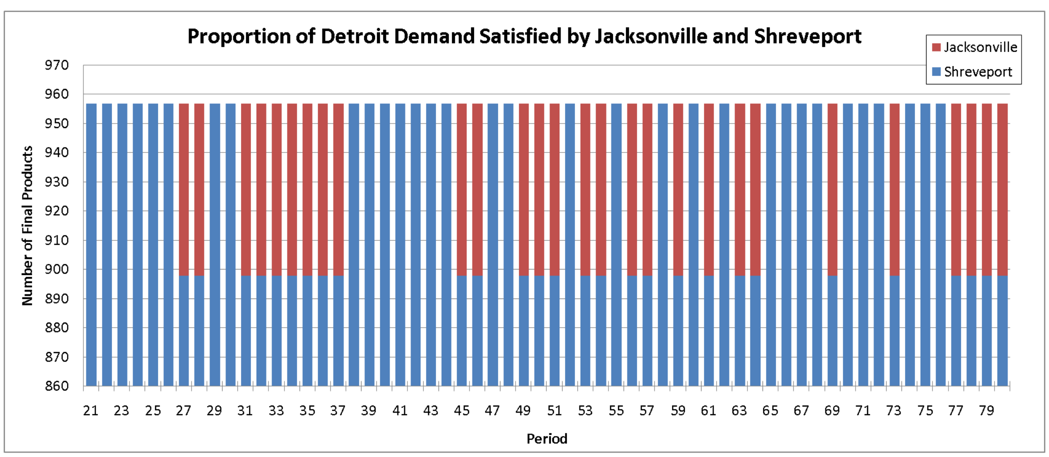


Figure 4.15: Case 4(b) - Detroit Demand

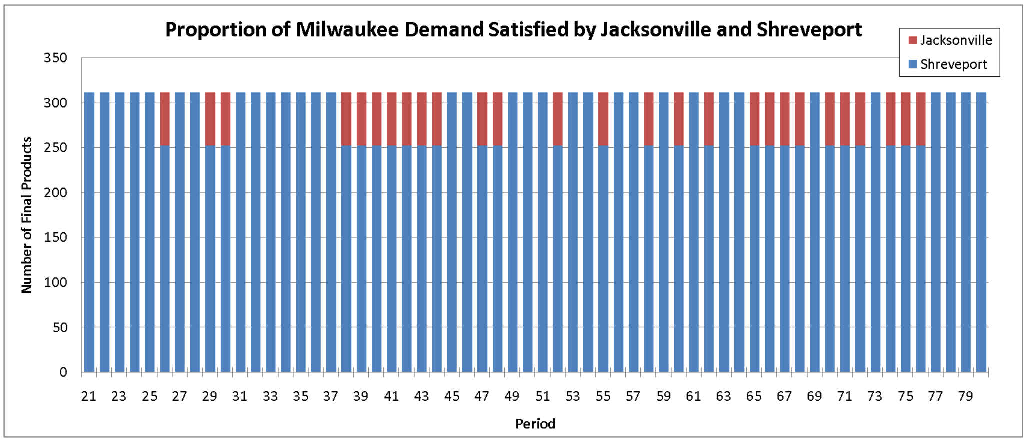


Figure 4.16: Case 4(b) - Milwaukee Demand

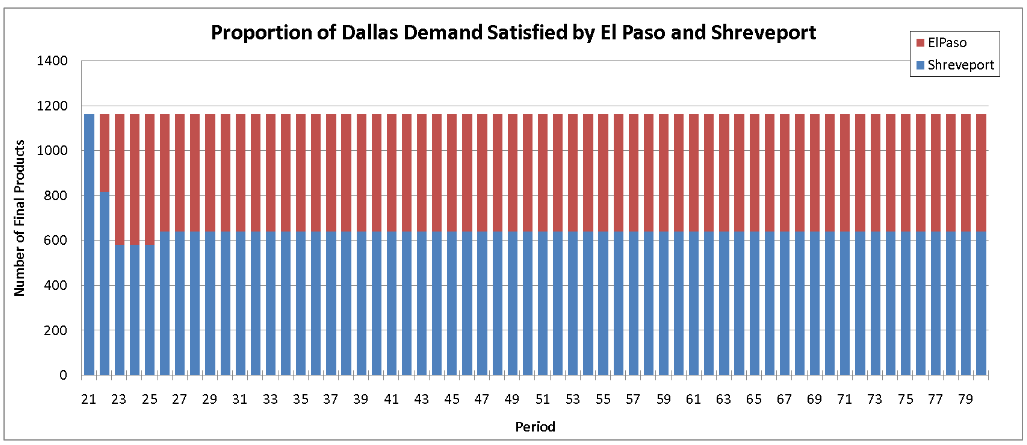


Figure 4.17: Case 4(b) - Dallas Demand

The assignment of supply from each DC to all customers is more consistent than in the base case. Generally, after $t = 25$, the total supply assiged levels out: 1852 units from both Shreveport and El Paso, and 1631 units from Jacksonville. El Paso supplies the same number of units to its customers each period (Figure 4.18), while there are only slight deviations for certain customers supplied by Jacksonville and Shreveport (Figures 4.19 and 4.20). In a given period, Jacksonville ships either 59 units to Detroit or Milwaukee, but never to both.

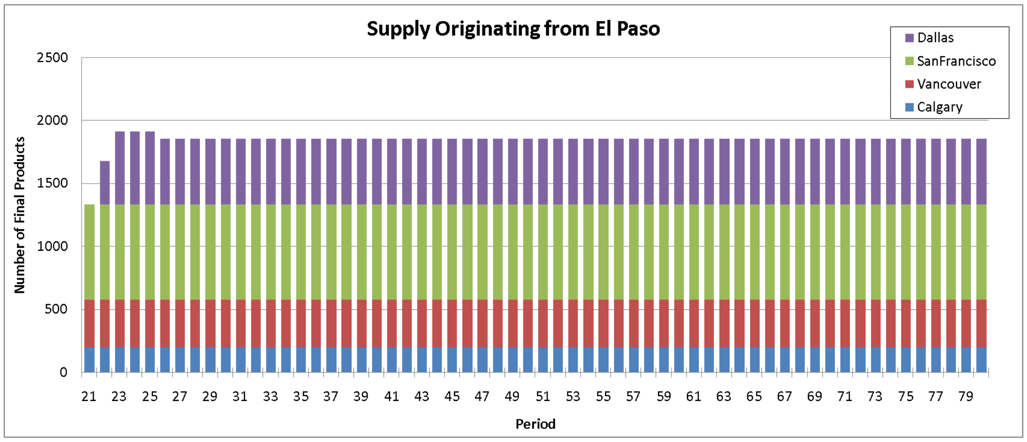


Figure 4.18: Case 4(b) - El Paso Supply

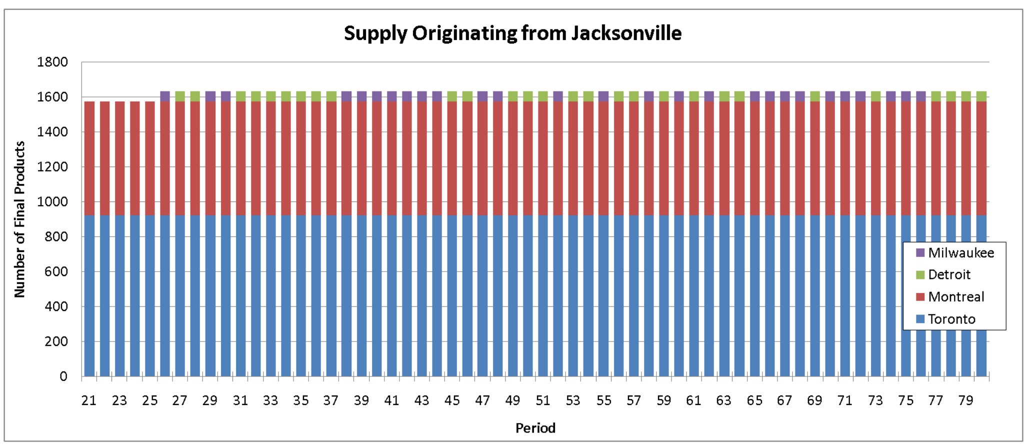


Figure 4.19: Case 4(b) - Jacksonville Supply

4.5.3 Case 4(c): Decreasing Winnipeg's Costs

With the imminent opening of CentrePort in Manitoba, Winnipeg becomes a viable DC location to serve both Canadian and U.S. customers. Its central location provides Winnipeg with access to major highways in both countries, and lends itself well as a transshipment point for goods traveling in any direction. Along with Kansas City's SmartPort, these *inland ports* are playing important roles by offering a multitude of logistics solutions (CentrePort Canada; KC SmartPort).

An inland port acts as a hub to receive, consolidate, and distribute material in one convenient location. In addition to alleviating congested port traffic on the western coasts of the U.S. and Mexico, SmartPort and CentrePort are designated *foreign trade zones* that offer attractive cost savings, such as reduced taxes and tariff exemptions. Locating a plant or DC near these inland ports would help save costs and also improve supply chain performance, given the proximity to these services.

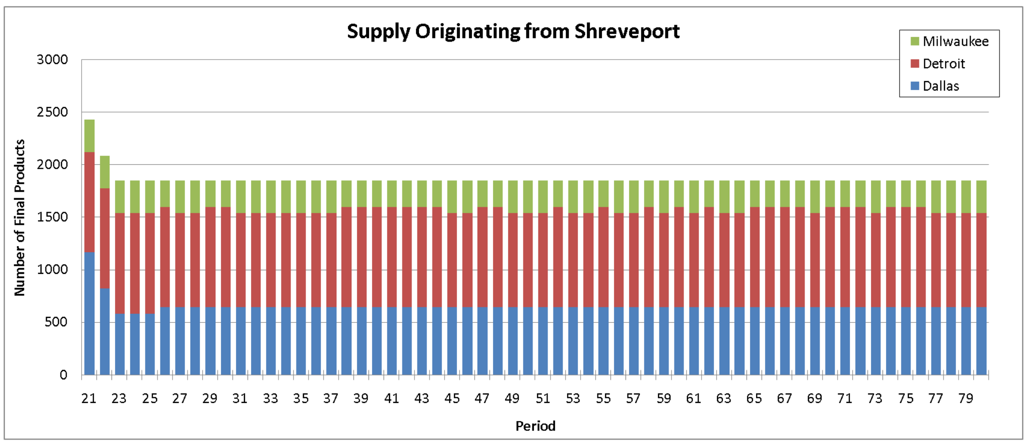


Figure 4.20: Case 4(b) - Shreveport Supply

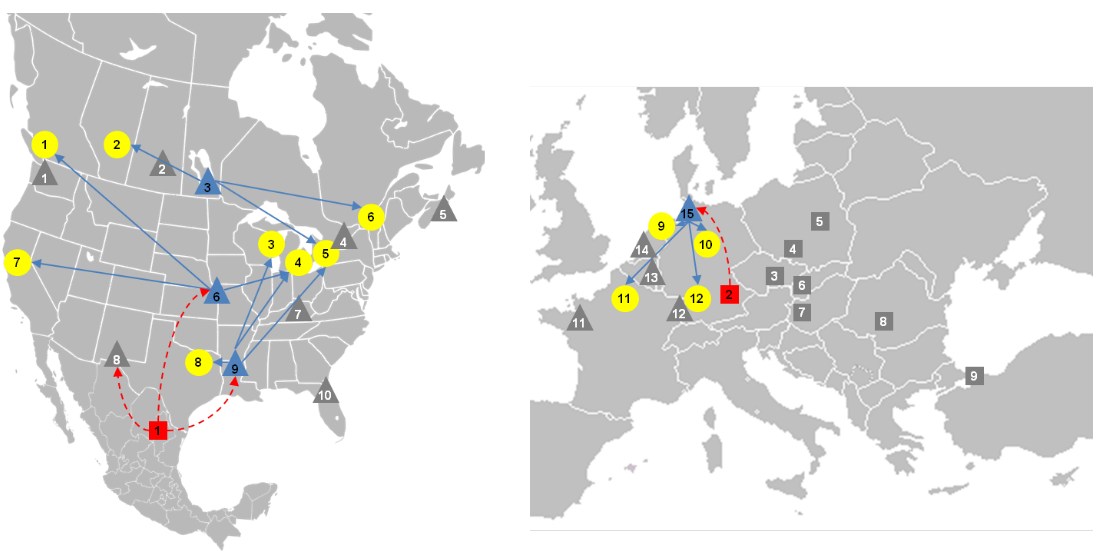


Figure 4.21: Network Configuration: Case 4(c) - Decreasing Winnipeg's Costs

For Winnipeg to enter into the model's solution, its costs must decrease by at least 1.06%. In this scenario, Winnipeg will serve Calgary, Toronto, and Montreal; Kansas City will serve Detroit, Vancouver and San Francisco; and Shreveport will support Toronto, Detroit, Dallas, and Milwaukee (Figure 4.21).

The DCs ship more consistent amounts to their customers, in contrast to the allocation patterns seen in the Base Case. By $t = 30$, the proportion of Toronto's demand satisfied by Winnipeg levels out to 784 units, with the remaining 135 units supplied by Shreveport (Figure 4.22). Similarly, Detroit has Shreveport and Kansas City supplying 241 and 716 units, respectively (Figure 4.23). The same pattern is seen from the DCs' perspectives, where consistent numbers of final products are shipped to each of their customers for the duration of the planning horizon (Figures 4.24 to 4.26).

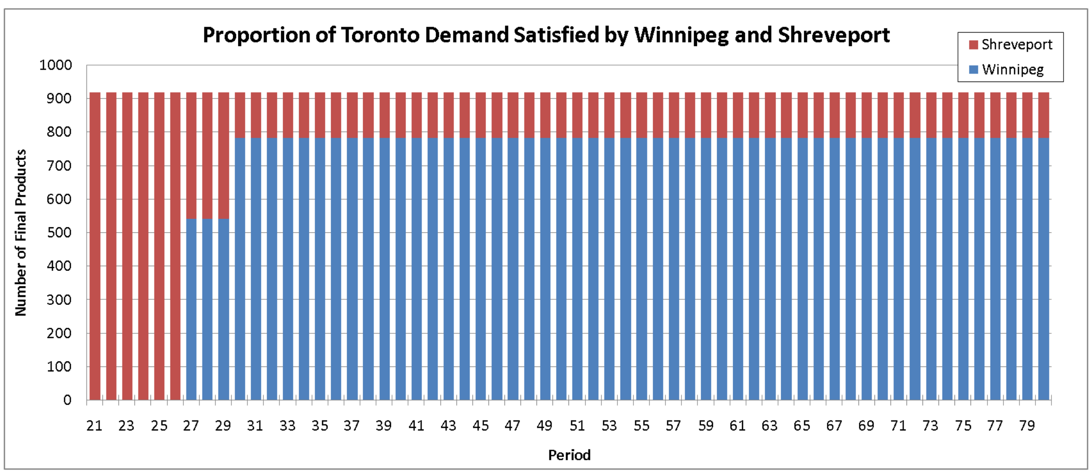


Figure 4.22: Case 4(c) - Toronto Demand

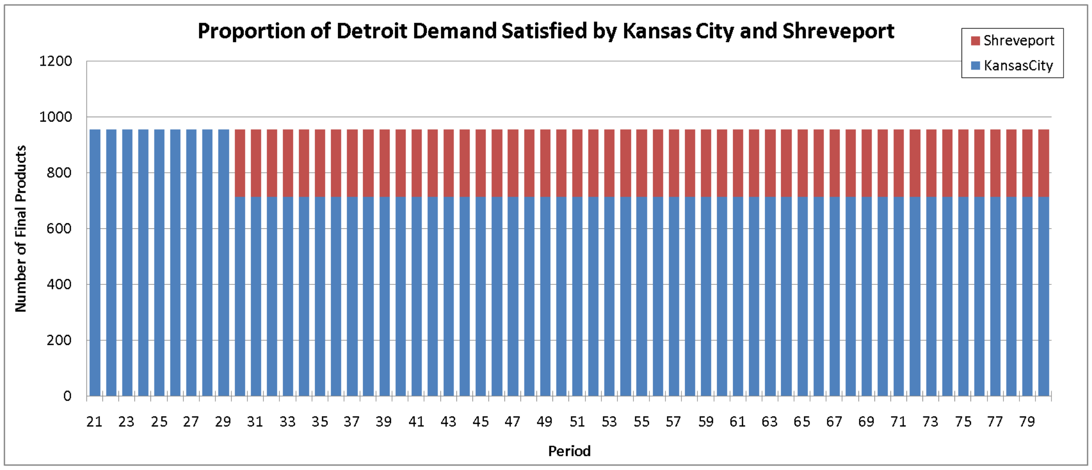


Figure 4.23: Case 4(c) - Detroit Demand

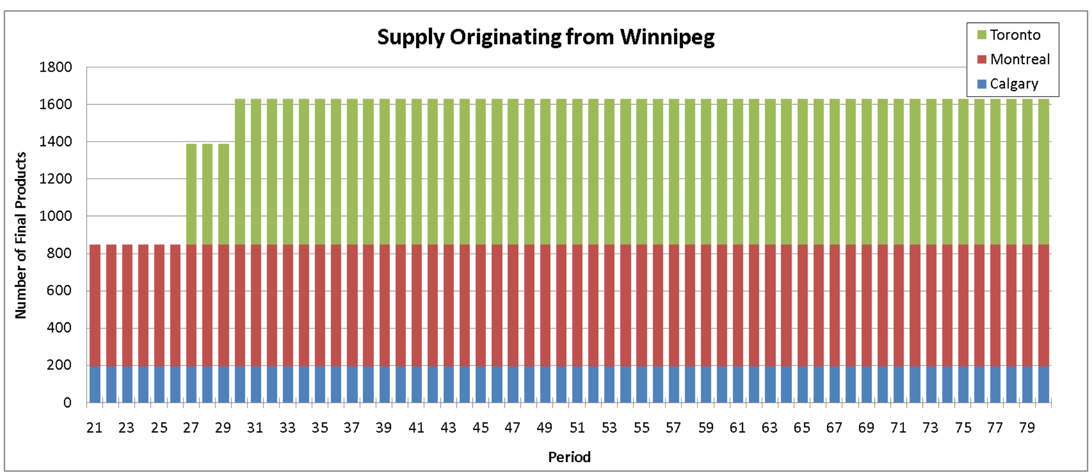


Figure 4.24: Case 4(c) - Winnipeg Supply

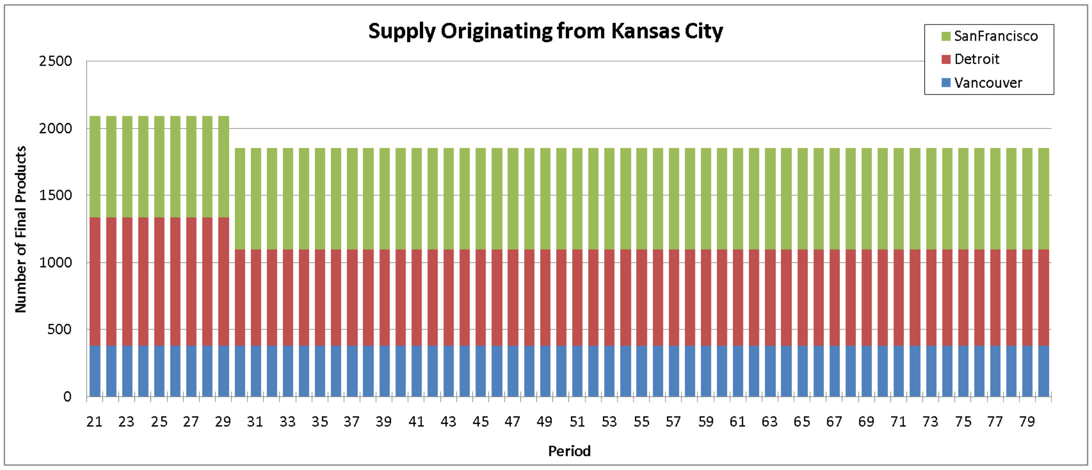


Figure 4.25: Case 4(c) - Kansas City Supply

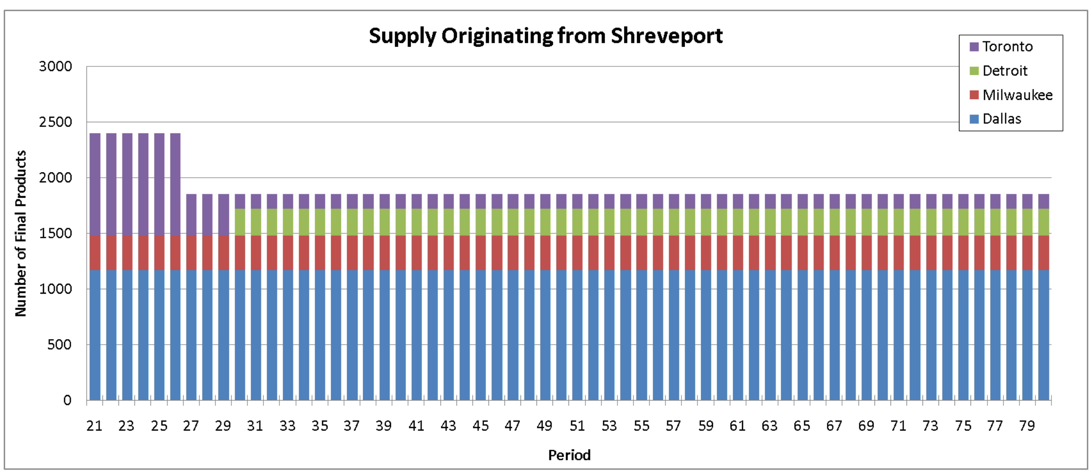


Figure 4.26: Case 4(c) - Shreveport Supply

4.6 Case 5: Varying Demand

We now examine the change in the network configuration when demand is varied in four different ways: seasonally, cyclically with all customers in phase, cyclically with groups of customers out of phase, and randomly.

4.6.1 Case 5(a): Seasonal Demand

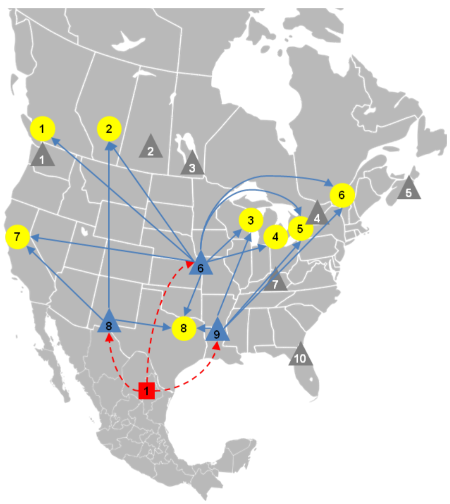
We assume that each customer has seasonal demand (Table 4.2). Again, we scale the demand for all the customers based on the factors listed in Table 4.1. In the early months of the year, demand is high, but then decreases slightly in periods $t = 5$ and $t = 6$. A summer shutdown in $t = 7$ lowers demand abruptly, but then it resumes and declines slowly until the last period. Daily demand for the operational model (OM) is calculated by dividing the monthly demand by 30 days. We increase the length of the OM planning horizon from $T = 60$ to $T = 360$ days to better model the operational characteristics of the network.

This scenario results in the same facilities being opened as in the Base Case, but the assignment of DCs to customers varies (Figure 4.27(i)). Kansas City now serves all customers at some point during the planning horizon, while El Paso has large spans of time where it is not used (Figure 4.28). Most customers are served by a combination of

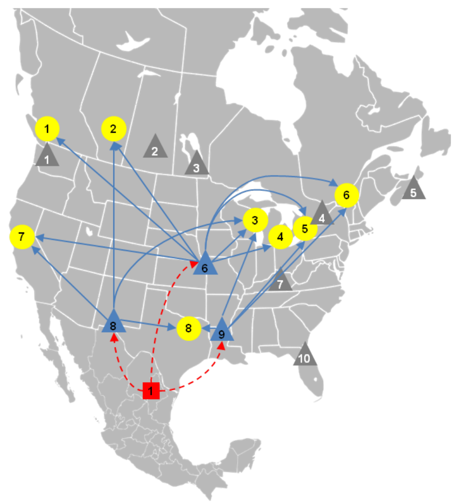
Period	**Van**	**Cal**	**Mil**	**Det**	**Tor**	**Mon**	**San**	**Dal**	**Wee**	**Han**	**Cer**	**Stu**
1	12 000	6 108	9 852	30 216	28 992	20 616	23 844	36 732	97	2 952	324	3 396
2	13 500	6 872	11 084	33 993	32 616	23 193	26 825	41 324	108	3 321	365	3 821
3	15 000	7 635	12 315	37 770	36 240	25 770	29 805	45 915	120	3 690	405	4 245
4	17 500	8 908	14 368	44 065	42 280	30 065	34 773	53 568	140	4 305	473	4 953
5	15 000	7 635	12 315	37 770	36 240	25 770	29 805	45 915	120	3 690	405	4 245
6	13 500	6 872	11 084	33 993	32 616	23 193	26 825	41 324	108	3 321	365	3 821
7	7 500	3 818	6 158	18 885	18 120	12 885	14 903	22 958	61	1 845	203	2 123
8	10 000	5 090	8 210	25 180	24 160	17 180	19 870	30 610	81	2 460	270	2 830
9	9 500	4 836	7 800	23 921	22 952	16 321	18 877	29 080	77	2 337	257	2 689
10	9 500	4 836	7 800	23 921	22 952	16 321	18 877	29 080	77	2 337	257	2 689
11	7 500	3 818	6 158	18 885	18 120	12 885	14 903	22 958	61	1 845	203	2 123
12	5 000	2 545	4 105	12 590	12 080	8 590	9 935	15 305	40	1 230	135	1 415

Table 4.2: Case 5(a): Seasonal Demand

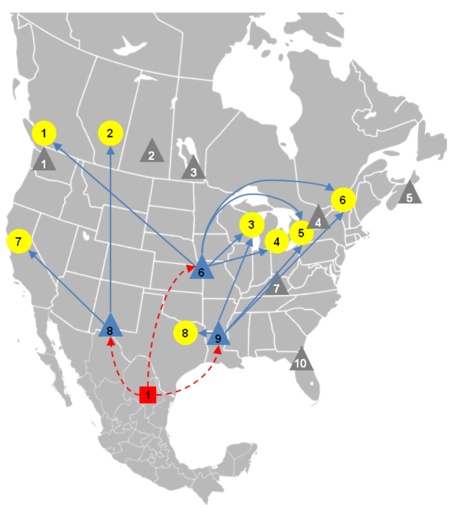
DCs in any period, except Calgary and Dallas. For Calgary, it is served by El Paso from $t \in [81, 170]$ only, and Kansas City at all other times. Shreveport is the main supplier for Dallas, shipping final products from $t \in [21, 350]$, with some help from Kansas City briefly in $t \in [201, 229]$ and again from $t \in [321, 380]$ (periods when demand is at its lowest), and El Paso $t \in [82, 170]$ (when demand is at its peak in the early part of the year).



(i) Cases 5(a) & (b) - Seasonal and Cyclical (In Phase) Demand



(ii) Case 5(c) - Cyclical Demand (Out of Phase)



(iii) Case 5(d) - Random Demand

Figure 4.27: NAFTA Network Configuration: Case 5 - Varying Demand Patterns

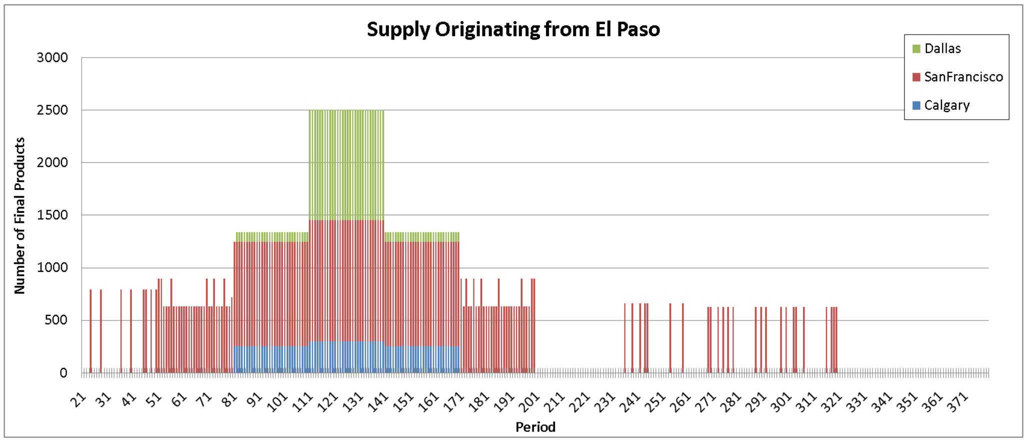


Figure 4.28: Case 5(a) - El Paso Supply

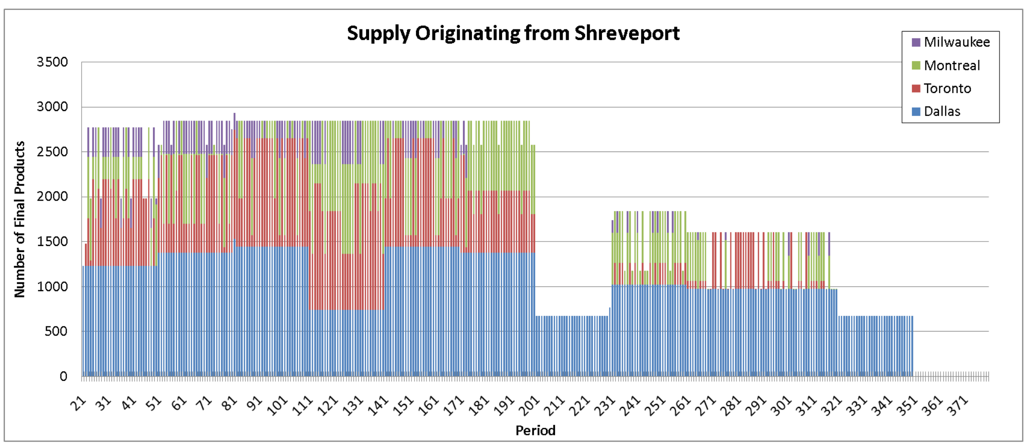


Figure 4.29: Case 5(a) - Shreveport Supply

Shreveport is in use until $t = 350$, after which it does not serve any customers (Figure 4.29). During these last 30 days, Kansas City assumes all supplying responsibilities, serving all customers. During the periods with lowest demand ($t \in [201-230] \cup [351, 380]$), the pattern of supply is more consistent, with Kansas City shipping the same amount to each customer over each 30-day interval (Figure 4.30).

Recall that in the Base Case, final products are held in Kansas City from $t \in [20, 22]$ in the amounts of 198, 2050, and 681 respectively. When there is seasonal demand, inventory

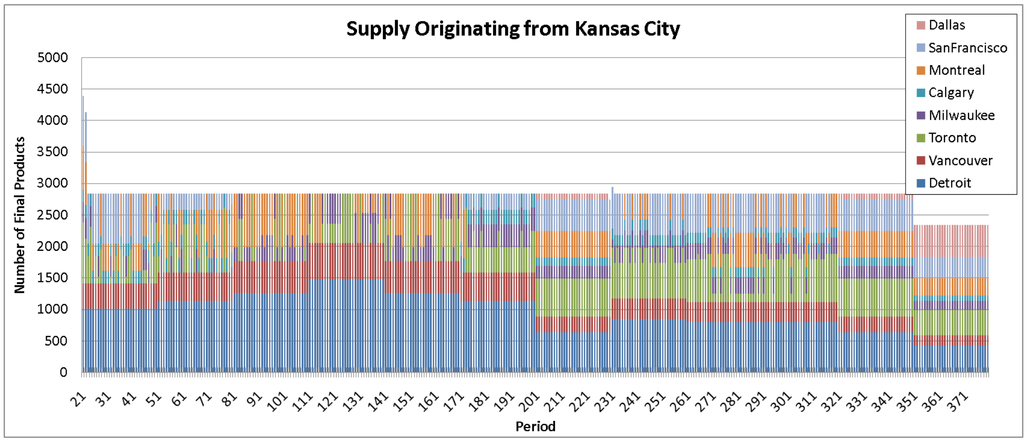


Figure 4.30: Case 5(a) - Kansas City Supply

is held in Kansas City for $t = 21, 22, 231$, and in Shreveport in $t = 81$. These correspond to periods when demand begins to rise. Production does not begin until $t = 16$, one period later than in the Base Case. No inventory is held in period $t = 20$ though, which may be the reason for the later start.

4.6.2 Case 5(b): Cyclical Demand (In Phase)

The demand in this scenario resembles a sinusoidal graph, whose highest demand is 15000 units, and lowest demand is 3000 units (for Vancouver, the reference customer). The period of the graph (from peak to peak) spans five months (time periods), meaning that the strategic planning horizon has a duration of 2.75 periods (Table 4.3).

Again, we see the same network configuration as in Case 5(a), with emphasis placed on the Kansas City DC, serving every customer in at least one period. It is in operation every period, with El Paso and Shreveport used in most periods but not all. When demand is at its lowest (the valley of the sinusoidal pattern), Shreveport is not in use. El Paso is at its most productive during periods of peak demand but only sporadically serves San Francisco (Figures 4.31 and 4.33). Final products are held in Kansas City and Shreveport in periods when demand is rising after experiencing low demand.

Period	Van	Cal	Mil	Det	Tor	Mon	San	Dal	Wee	Han	Cer	Stu
1	15 000	7 635	12 315	37 770	36 240	25 770	29 805	45 915	120	3 690	405	4 245
2	9 000	4 581	7 389	22 662	21 744	15 462	17 883	27 549	73	2 214	243	2 547
3	3 000	1 527	2 463	7 554	7 248	5 154	5 961	9 183	24	738	82	849
4	9 000	4 581	7 389	22 662	21 744	15 462	17 883	27 549	73	2 214	243	2 547
5	15 000	7 635	12 315	37 770	36 240	25 770	29 805	45 915	120	3 690	405	4 245
6	9 000	4 581	7 389	22 662	21 744	15 462	17 883	27 549	73	2 214	243	2 547
7	3 000	1 527	2 463	7 554	7 248	5 154	5 961	9 183	24	738	82	849
8	9 000	4 581	7 389	22 662	21 744	15 462	17 883	27 549	73	2 214	243	2 547
9	15 000	7 635	12 315	37 770	36 240	25 770	29 805	45 915	120	3 690	405	4 245
10	9 000	4 581	7 389	22 662	21 744	15 462	17 883	27 549	73	2 214	243	2 547
11	3 000	1 527	2 463	7 554	7 248	5 154	5 961	9 183	24	738	82	849
12	9 000	4 581	7 389	22 662	21 744	15 462	17 883	27 549	73	2 214	243	2 547

Table 4.3: Case 5(b): Cyclical Demand (In Phase)

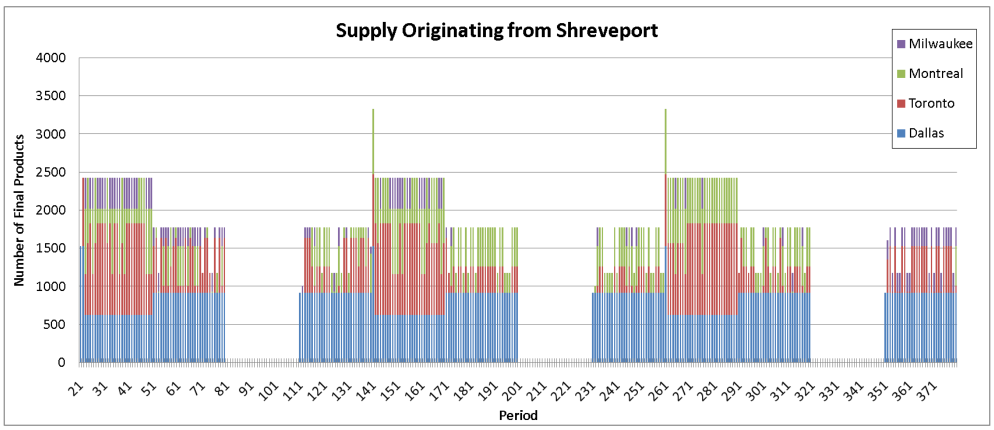


Figure 4.31: Case 5(b) - Shreveport Supply

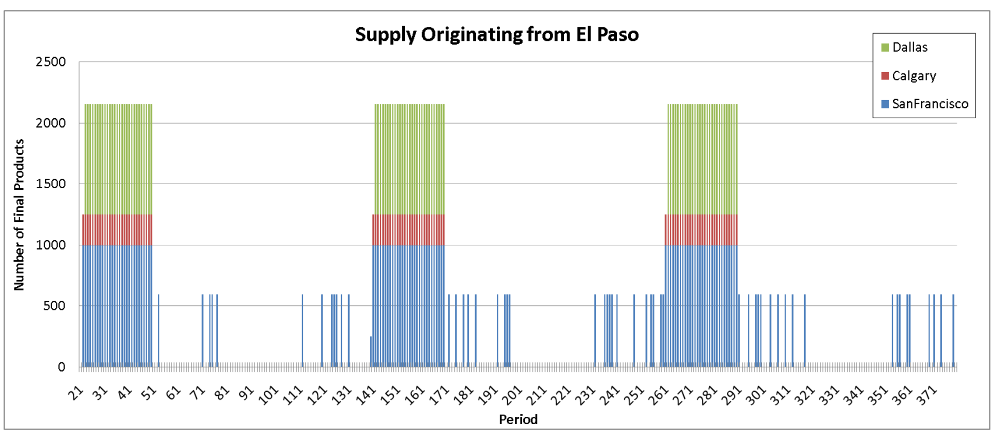


Figure 4.32: Case 5(b) - El Paso Supply

4.6.3 Case 5(c): Cyclical Demand (Out of Phase)

We group customers by geographic region and adjust their demand accordingly, using the same sinusoidal graph from Case 5(b), but shifting its phase to the right (Table 4.4). Vancouver is again used as the reference demand and is grouped with San Francisco (west coast). Calgary and Dallas, in central North America, will be shifted to the right by $\frac{1}{4}$ phase. Milwaukee, Detroit, and Toronto are shifted $+\frac{1}{2}$ phase, and Montreal $+\frac{3}{4}$ phase. For European customers, we group Cergy and Stuttgart and keep them in phase with Vancouver, but shift Hannover and Weesp $+\frac{1}{4}$ phase.

Kansas City serves all customers except Dallas (Figure 4.27(ii)). Each DC in the NAFTA region is active over the entire planning horizon, with El Paso having a more consistent supply pattern than the others (Figure 4.33). Kansas City sends end items to Detroit and Vancouver following a regular pattern, but does supply other customers to satisfy their demand during peak periods (Figure 4.34).

Inventory is held in Kansas City when $t = 21, 22$ and in Shreveport for $t = 81, 201, 321$. This is likely due to the smaller range of demand in this scenario than when all customers are in the same phase of the cyclical demand pattern. There is a more steady stream of products flowing when certain customers are in their peak season, others are not.

Period	**Van**	**Cal**	**Mil**	**Det**	**Tor**	**Mon**	**San**	**Dal**	**Wee**	**Han**	**Cer**	**Stu**
1	15 000	4 581	2 463	7 554	7 248	15 462	29 805	27 549	73	2 214	405	4 245
2	9 000	1 527	7 389	22 662	21 744	25 770	17 883	9 183	24	738	243	2 547
3	3 000	4 581	12 315	37 770	36 240	15 462	5 961	27 549	73	2 214	82	849
4	9 000	7 635	7 389	22 662	21 744	5 154	17 883	45 915	120	3 690	243	2 547
5	15 000	4 581	2 463	7 554	7 248	15 462	29 805	27 549	73	2 214	405	4 245
6	9 000	1 527	7 389	22 662	21 744	25 770	17 883	9 183	24	738	243	2 547
7	3 000	4 581	12 315	37 770	36 240	15 462	5 961	27 549	73	2 214	82	849
8	9 000	7 635	7 389	22 662	21 744	5 154	17 883	45 915	120	3 690	243	2 547
9	15 000	4 581	2 463	7 554	7 248	15 462	29 805	27 549	73	2 214	405	4 245
10	9 000	1 527	7 389	22 662	21 744	25 770	17 883	9 183	24	738	243	2 547
11	3 000	4 581	12 315	37 770	36 240	15 462	5 961	27 549	73	2 214	82	849
12	9 000	7 635	7 389	22 662	21 744	5 154	17 883	45 915	120	3 690	243	2 547

Table 4.4: Case 5(c): Cyclical Demand (Out of Phase)

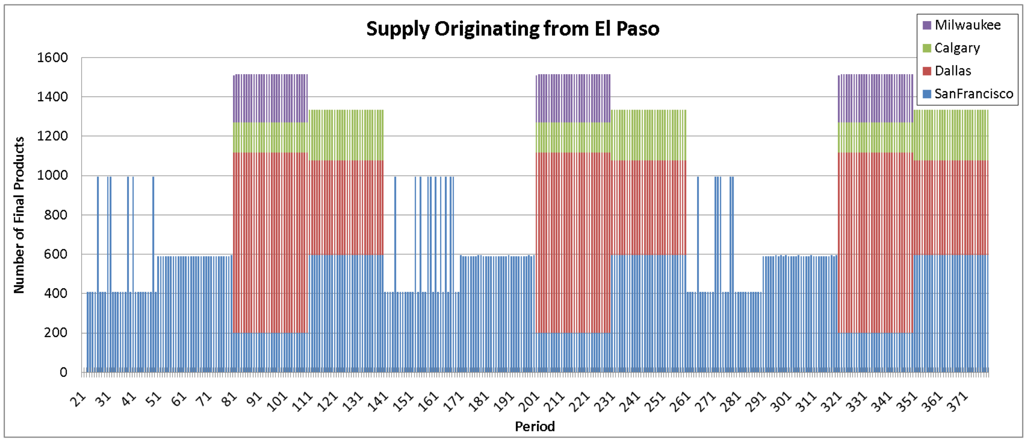


Figure 4.33: Case 5(c) - El Paso Supply

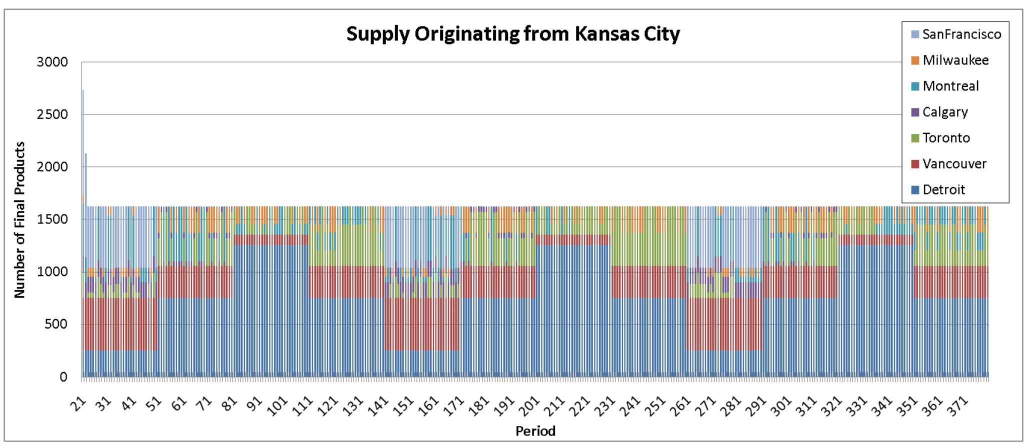


Figure 4.34: Case 5(c) - Kansas City Supply

4.6.4 Case 5(d): Random Demand

A random number generator (Urbaniak and Plous, 2008) is used to determine the daily demand for OM (Table 4.5). The uniform demand distribution is characterized by $U[0, b]$, with b adjusted to ensure that they are consistent with the relative population size of each customer city. The values of b are listed in Table 4.6.

With random demand, we obtain a very similar network configuration as in the Base Case. Dallas serves the same five customers, but El Paso serves only Calgary and San

Period	**Van**	**Cal**	**Mil**	**Det**	**Tor**	**Mon**	**San**	**Dal**	**Wee**	**Han**	**Cer**	**Stu**
1	5 759	2 770	4 120	16 339	13 361	9 624	11 841	16 701	774	1 650	715	2 090
2	7 363	2 982	4 527	15 187	12 148	8 588	11 103	20 051	717	1 346	772	2 459
3	5 734	2 944	4 202	15 319	13 859	6 511	12 055	19 838	757	1 660	765	2 255
4	5 414	3 007	4 296	16 791	14 689	8 617	10 859	15 364	850	1 415	703	2 588
5	6 517	2 708	4 429	14 687	14 832	12 703	11 220	18 406	772	1 604	678	2 092
6	5 524	2 885	4 310	15 308	13 613	11 109	11 972	17 484	739	1 496	708	2 408
7	6 671	2 630	5 456	12 339	12 917	9 737	11 245	16 849	792	1 411	741	2 386
8	6 095	3 313	4 283	14 252	15 097	10 109	10 700	17 369	778	1 417	635	2 553
9	5 359	2 752	3 998	13 525	14 511	10 345	11 737	18 699	887	1 520	760	2 379
10	6 112	3 360	4 806	18 393	14 769	11 063	10 144	16 200	707	1 420	703	2 166
11	6 419	2 934	4 505	16 272	12 719	11 892	11 302	17 045	759	1 491	771	2 202
12	4 968	2 463	4 038	13 266	14 329	9 922	12 259	20 754	680	1 232	791	1 963

Table 4.5: Case 5(d): Random Demand

City	**Upper Bound, b**
Vancouver	400
Calgary	200
Milwaukee	300
Detroit	950
Toronto	950
Montreal	650
San Francisco	750
Dallas	1200
Weesp	50
Hannover	100
Cergy	50
Stuttgart	150

Table 4.6: Case 5(d): Upper Bound on Random Demand

Francisco (Figure 4.27(iii)). Patterns in demand are not as clearly established, due to the random nature of demand (Figure 4.35). Unlike other cases examined thus far, more inventory is held through the entire planning horizon (Figure 4.36).

4.7 Case 6: "Unfix" Monterrey

In the preceding cases, we assumed that the manufacturing plant in Monterrey was fixed and set $V_{Monterrey} = 1$. Now, we relax this assignment and allow the model to choose where the manufacturing plant(s) shall be located.

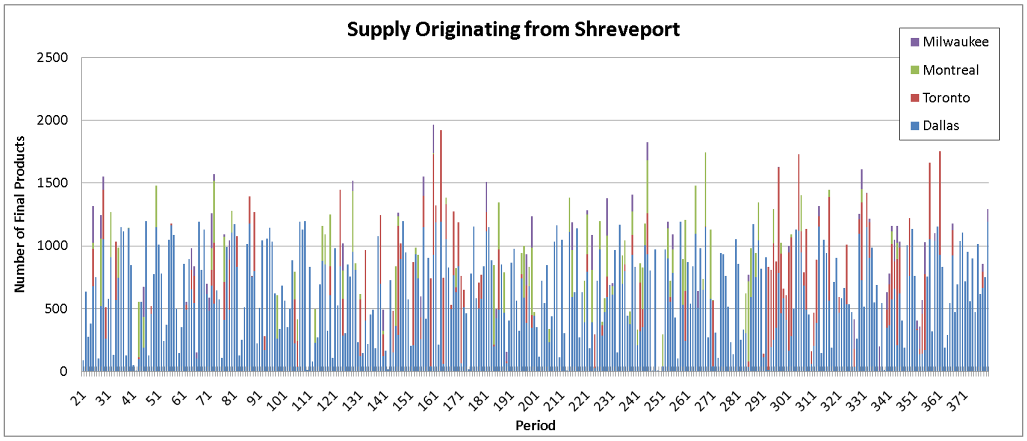


Figure 4.35: Case 5(d) - Shreveport Supply

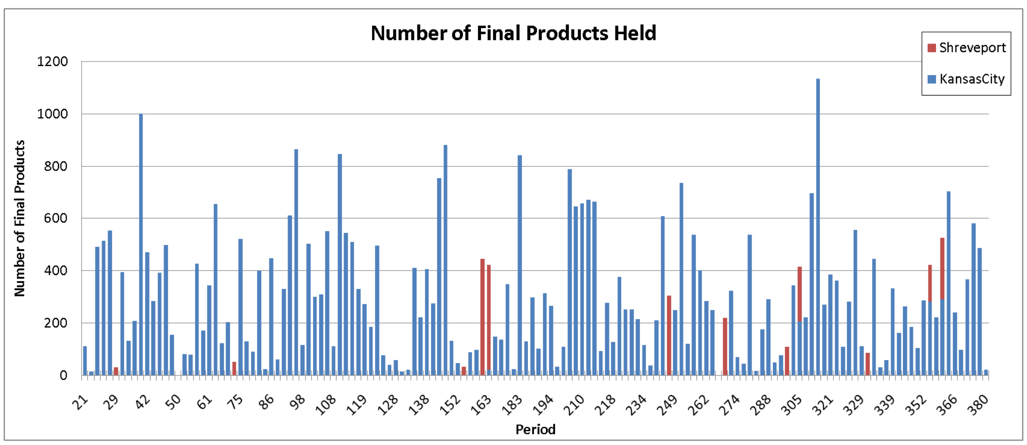


Figure 4.36: Case 5(d) - Inventory Held

4.7.1 Case 6(a): Relaxing the Number of EU Plants

In Case 6(a), we keep the initial locations shown in Figure 3.1, but remove Equation 3.3. The model chooses Monterrey as the only plant, serving Emden by ocean, and Kansas City, Shreveport, and El Paso by rail. The DC-customer allocations remain the same as in the Base Case (Figure 4.37). With Monterrey shipping by ocean, production at this plant begins earlier, at $t = 5$, to accommodate for the lengthy lead time to Emden.

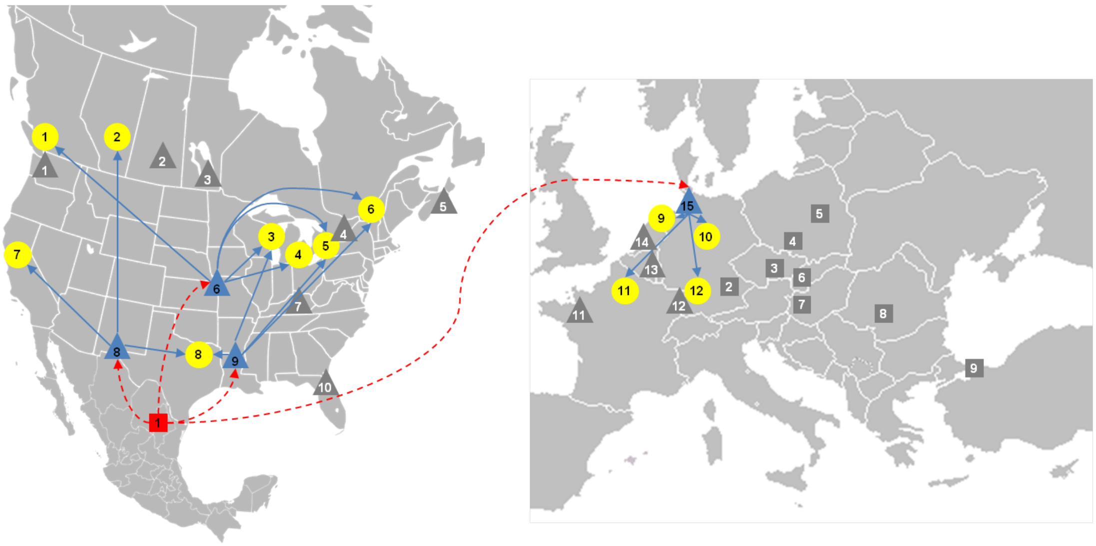


Figure 4.37: Case 6(a) - Relaxing the Number of EU Plants

4.7.2 Case 6(b): Introducing New Potential Plant Locations

In Case 5(b), we introduce a number of potential NAFTA plant locations: Guadalajara, Mexico; Windsor, Ontario; Columbus, Ohio. With these new locations, we: (i) allow any number of plants to be located anywhere; (ii) force the model to locate one plant in NAFTA and one in the EU; and (iii) force the model to locate two plants but in any or both regions.

In Case 6(b-i), we allow the model to locate any number of plants in any region, as in Case 6(a) above. Columbus is chosen as the only manufacturing facility, shipping to Guipry, France by ocean and Oshawa, Kansas City, and Lexington by rail. The EU customers are served by rail, as are all customers in the NAFTA region, except Toronto, which is serviced by truck from Oshawa (Figure 4.38). Production begins in period $t = 10$, and inventory is held in Lexington from $t = 20$ through 23.

In Case 6(b-ii), we restrict the model to choose one plant in the EU and one in the NAFTA region (i.e. reintroduce Equation 3.3, as well as Equation 4.3 below). The resulting network has plants in Regensburg and Columbus, with the DC-customer links resembling a mix of the Base Case for the EU and Case 6(b-i) for NAFTA (Figure 4.39).

$$\sum_{i \in I_2} V_i = 1 \qquad (4.3)$$

For the third modification, we stipulate that two plants must be chosen, but they can be in any region. This results in the same network as Case 6(b-ii).

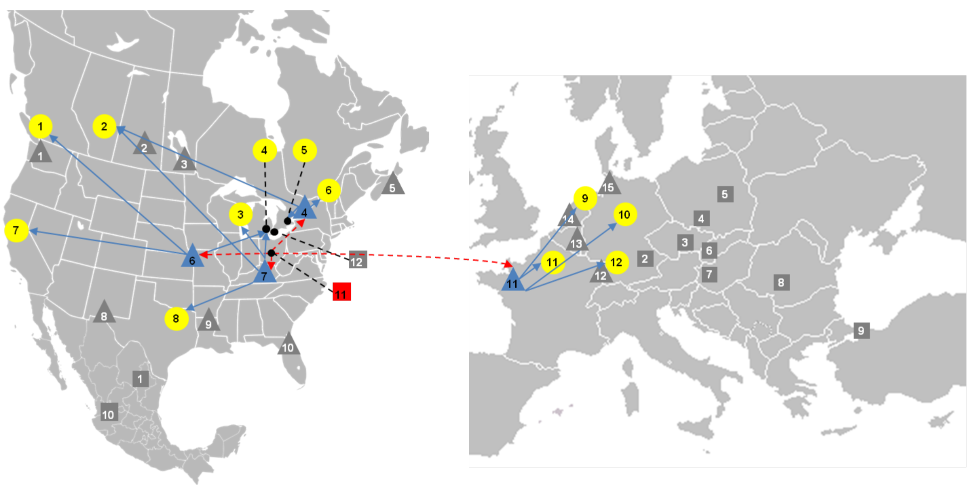


Figure 4.38: Case 6(b-i) - Any Number of Plants in Any Region

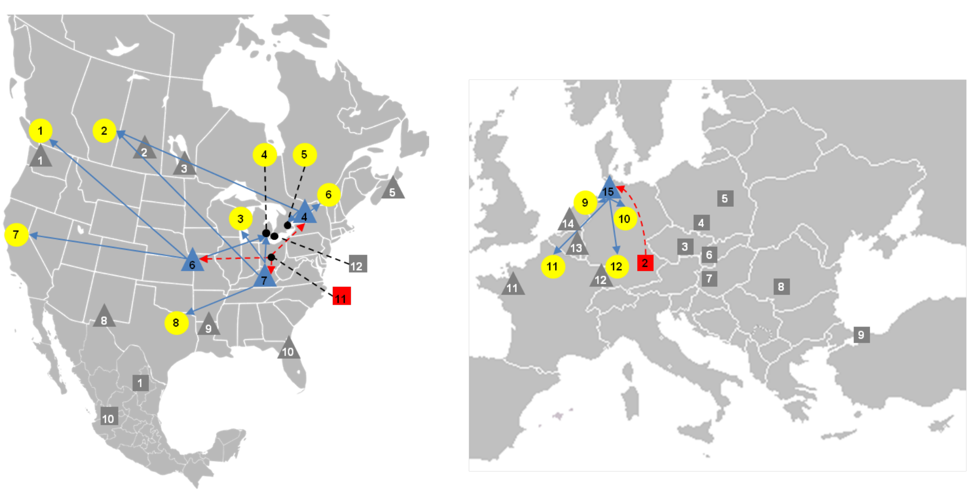


Figure 4.39: Case 6(b-ii) - One Plant in NAFTA, One Plant in the EU

4.8 Case 7: Relaxing the DC-Customer Assumption

4.8.1 Case 7(a): Revised Base Case

Up to now, DCs were restricted to serve only customers in their respective regions. Using the Base Case model, but relaxing this condition, we find that Hluk and Monterrey are the chosen plants, except that Hluk is never in operation (recall that in the Base Case, the model *must* choose an EU plant location, and Monterrey is already open by default) (Figure 4.40).

Kansas City serves Vancouver and Detroit, and shares Milwaukee, Toronto, and Montreal with Shreveport. El Paso ships final products to Dallas, San Francisco, and Calgary by rail, and to all EU customers by ocean. Production begins earlier, when $t = 15$, to allow time to build up inventory.

4.8.2 Case 7(b): Unfixing Monterrey and Relaxing Equation 3.3

As in Case 6(a), we allow the model to choose any number of plants in any region. The model chooses Monterrey as the sole operating plant, and keeps Kansas City, Shreveport, and El Paso as DCs (Figure 4.41). The DC-Customer allocations remain the same as in Case 7(a).

4.8.3 Case 7(c): Guadalajara, Windsor, and Columbus

Introducing these three new locations, and allowing any number of plants to be opened, we obtain a new network with Columbus as the manufacturing plant, and Oshawa, Kansas City, and Lexington as DCs (Figure 4.42). Oshawa serves all European customers by ocean and Toronto by truck. All other customers are served by rail.

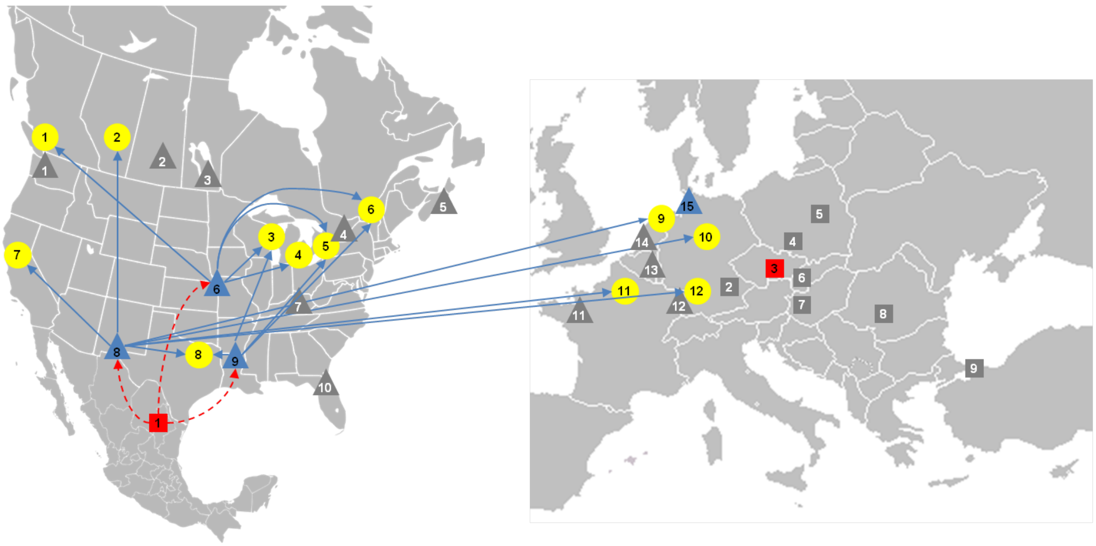


Figure 4.40: Case 7(a) - Inter-FTZ Allocations

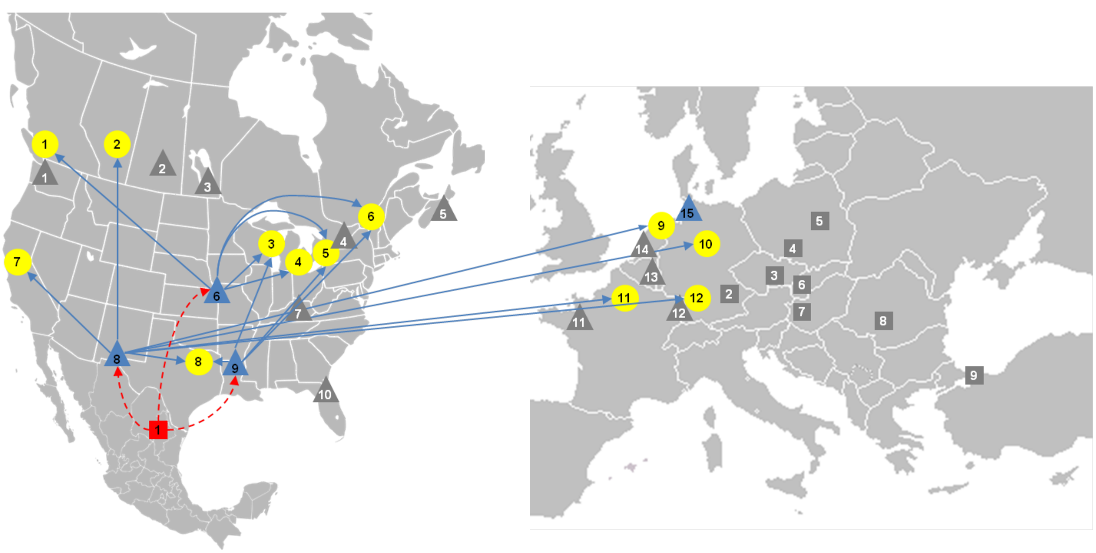


Figure 4.41: Case 7(b) - Unfixing Monterrey and EU Plant Restrictions

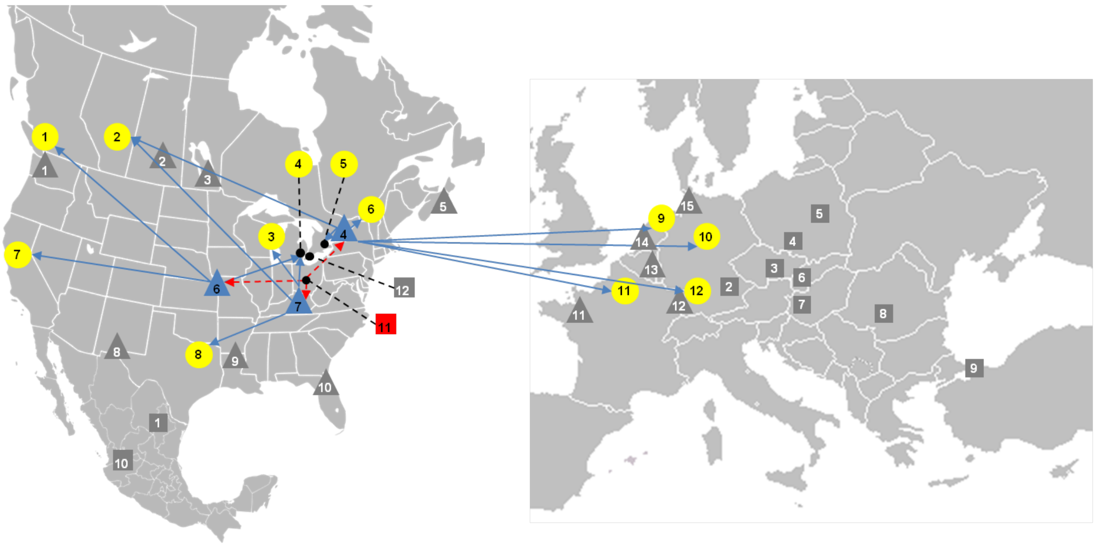


Figure 4.42: Case 7(c) - Adding New Potential Plant Locations

4.9 Case 8: Combining Cases

Rather than change only one parameter at a time, here we combine a number of variations in one scenario. We examine the effect of changes on tax rates, fixed and variable costs, demand patterns, added potential plant locations, and allowing DCs to serve customers in any FTZ.

Using results from previous cases as our initial starting points, we modify the fixed and variable costs of the Winnipeg and Emden DCs. Decreasing Winnipeg's costs by more than 1.75% and increasing Emden's by more than 0.7% results in two plants being located, in Tychy and Columbus. DCs are in Rotterdam, Winnipeg, and Lexington (Figure 4.43). The Rotterdam DC also serves some NAFTA customers, in addition to the four EU customers.

We then vary demand, using the random data generated in Case 5(d). Only EU locations are chosen: Tychy for the manufacturing plant, and Genk, Emden and Rotterdam for the DCs (even with Emden's increased costs). This configuration is not realistic, as the European DCs ship all products to North American customers by ocean as it is the cheapest mode. This would not be a viable option if lead times were included, so we rein-

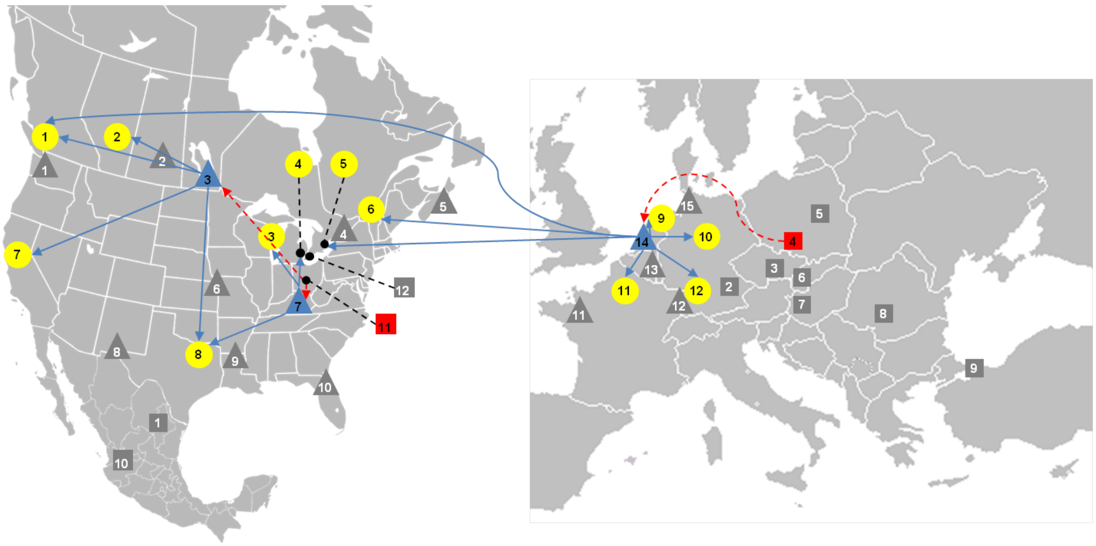


Figure 4.43: Case 8(a) - Using Actual Interest Rates and Varying Costs for Winnipeg and Emden

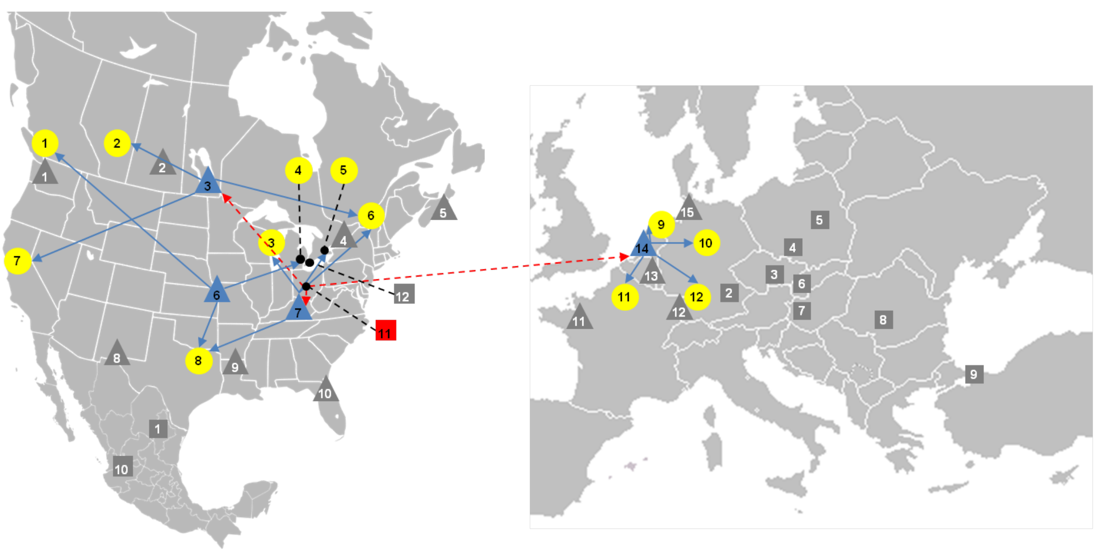


Figure 4.44: Case 8(b) - Actual Interest Rates, Varied DC Costs and Random Demand

troduce restrictions on DC-Customer links, allowing only EU (NAFTA) DCs to serve EU (NAFTA) customers. This produces a network similar to that in Figure 4.43, but with Columbus as the only manufacturing plant and an added DC in Kansas City (Figure 4.44).

Finally, we examine the effect of varied transfer prices by increasing them on non-FTZ links, as in Case 2. When DCs are allowed to serve customers in any region, the manufacturing plant location is in Istanbul, where higher transfer prices are being charged to DCs but also where lower tax rates are available. Istanbul ships material to Emden, Rotterdam, and Strasbourg, whose tax rates are higher.

Again, the previous network is not very realistic, with the long lead times from Europe to North America, so we enforce the restrictions on DC-Customer links. No changes occur when transfer prices are increased: Columbus is still the only plant that serves Rotterdam, Winnipeg, Lexington, and Kansas City. We deduce that transfer prices have only a little effect on this network as most transactions occur between countries with very similar tax rates, thus "canceling out" any revenues or expenses arising from the internal sales.

Chapter 5

Conclusion

5.1 Summary of Numerical Results

We developed a mixed integer linear model to determine optimal network configurations and modal choices for a company operating in two free trade zones. The solution to such a problem depends upon the international factors considered. In this work, we included the tax rates for each country, as well as a transfer price charged for internal transactions. To maximize the company's total after-tax profit, the plants and DCs are located in countries with lower tax rates, and the routes chosen use the cheapest mode possible, subject to transportation and inventory holding costs. Our solution procedure was divided into two parts: first, we found plant and DC locations based on the monthly demand for one year. Using these locations, we then found the plant-DC and DC-customer allocations and the mode by which sub-assemblies and final products travel.

For each of Cases 1 through 7, we changed only one parameter, ranging from fixed and variable costs to demand. We modified each parameter value slightly to determine at which points the network obtained in the Base Case would change. In most cases, only minor fluctuations in parameter values affected plant/DC locations or customer demand allocations (e.g. Sections 4.2, 4.4, and 4.5). This indicates that care must be taken in choosing these values, that they accurately reflect the situation being modeled so that the model will provide a realistic result.

In Case 5, we examined a number of different demand scenarios and found that while the same plant and DC locations remain open, most differences occur between DC and customer allocations, i.e. "back-up" DCs were assigned to customers to supplement the main DC in periods of high demand.

Model assumptions for plant locations were relaxed in Case 6, allowing any number of manufacturing plants to be located in any region. In general, only one plant is needed to satisfy customer demand, but when forced to open two plants, the model will locate one in North America and the other in Europe. This occurs in Case 7(a), when we allowed DCs to serve customers in any region; the plant in Tychy, Poland is constrained to be open but manufactures nothing over the entire planning horizon.

For all scenarios in Case 7, the NAFTA DCs serve customers in the EU by ocean, as it is cheaper than shipping by air. While this may be appropriate for sitations with predictable demand, it would not provide timely shipments for urgent orders. Similar solutions appear in Case 8, when we combined a number of changes to parameters and relaxed certain constraints all at once.

When variations in transfer prices were included in Case 8, the solution changed, unlike in Case 2 where fluctuations in either direction (positive or negative) had no effect on the Base Case solution. This change in the solution was attributed to the fact that the tax rate for each country was set to 25%, and any profit incurred in one country would be offset by an equal expense in another. When actual tax rates were used, we were able to show that they and transfer prices will affect location decisions.

5.2 Contributions and Future Research

In this work, we were able to combine aspects from Wilhelm et al. (2005) and Robinson and Bookbinder (2007) into a single framework, by considering bill of materials constraints and lead times within a location and transportation model. International factors, such as income tax rates and transfer pricing, were also considered to show their effect on determining optimal network configurations and modal choices in a global setting.

Since locating facilities involves high investment costs, it is logical to assume that facility location decisions are strategic in nature and will not change as frequently as a production schedule. In contrast, the selection of transportation modes and routes are easily varied from period to period with minimal disruption in company operations. For these reasons, the strategic and operational nature of the supply chain are examined in sequence; facility locations are determined first, and will represent the nodes in the transportation problem that follows. Using a mixed integer linear program and "separating" the location and transportation decisions allowed for fast solution times without the use of decomposition, but has also left room to explore more complicated features of global supply chains where more sophisticated solution techniques could be employed.

The first area for future research includes the selection of parameter values. Though this work is based on a fictional company, there are many industries seeking to expand their global presence. To better serve these firms, a clear understanding and accurate representation of their costs is needed to produce a realistic solution.

While we assume that duties are included in transportation costs, it may be beneficial to treat them separately to examine their effect on profits. In Vidal and Goetschalckx (2001) and Wilhelm et al. (2005), tariffs are explicitly used as parameters and tax brackets are used to apply graduated tax rates to company earnings. This may help with the formulation and solution of the model when transfer prices are considered as decision variables. An attempt was made in this work to alter the model and replace the $\tau_{ijs}X_{ijmst}$ term in the objective function with a new variable, $\psi_{ijs} = \tau_{ijs}X_{ijmst}$. Once the model was solved, however, all values of ψ_{ijs} were zero (but $X_{ijms}(t)$ terms were not), indicating that all transfer prices were equal to zero. Upon closer investigation and manual adjustments to the transfer prices, we found that unlike Vidal and Goetschalckx (2001), net income after tax for the company continually decreased as transfer prices increased. This suggests that modifications need to be made to the current formulation to better model transfer price effects.

Other recommendations include the treatment of lead times from distribution centers to customers. We did not consider the transit time in this model, but feel that its presence would have a significant effect on location choices. International shipments by ocean may be cheaper than by air, but will contribute to higher pipeline inventory costs while in transit. Accordingly, the value chosen for pipeline inventory costs will also have effect on modal choice: as pipeline inventory cost increases, faster modes will be chosen to avoid penalties. A small test was conducted, where costs were increased from $1/cwt to $3/cwt, and resulted in the model choosing to ship by truck from Monterrey to El Paso and Shreveport rather than by rail.

Local content rules for each free trade zone should also be considered, especially for product flow between the EU and NAFTA. As there are currently no trade agreements between these FTZs, it would be interesting to test some potential tariff policies to gain insight on how a "super-FTZ" may impact international trade. Additional constraints and parameters would be required to dictate when material would qualify for tariff exemptions.

As the model changes with these additional features, a new solution methodology may be needed to either reduce complexity arising from non-linear terms or speed up solution time. Lagrangian relaxation would provide a good start, as the model is logically divisible into facility location and transportation subproblems. Benders decomposition may also be a valid solution approach, with location decisions requiring integer variables and the material flows using continuous variables. However, the ease of solution will be heavily dependent on the tractability of the subproblems.

Once the deterministic setting has been investigated thoroughly, future work may include probabilistic parameters that reflect the uncertainty in demand and lead times. The goal of that work would be to find a robust solution that fluctuates only slightly when subject to external volatility.

APPENDICES

Appendix A

Base Case Data

Unless otherwise noted, values listed in each table are assigned to each plant i, DC j, customer k, or country c.

A.1 Inventory Parameters

Inventory parameters include the maximum inventory and throughput levels allowed at each plant and DC.

Parameter	**Parts per month (SM)**	**Parts per day (OM)**
n_{i1}	543 072	18 240
n_{i2}	1 084 144	36 480
$\tilde{n}_{j1}$	90 512	3 040
$\tilde{n}_{j2}$	181 024	6 080
$\tilde{n}_j$	90 512	3 040

Table A.1: Maximum Inventory Levels

Parameter	Parts per month (SM)	Parts per day (OM)
w_{i1}	271 536	9 120
w_{i2}	543 072	18 240
$\tilde{w}_j$	45 256	1 520

Table A.2: Maximum Throughput

A.2 Cost Data

Listed below are the fixed costs by facility type, production and assembly costs, as well as holding and pipeline inventory costs.

Facility Type	$ per month (SM)	$ per day (OM)
Plant	19 153	642
DC	25 021	839

Table A.3: Fixed Costs by Facility Type

Parameter	$ per unit
q_{i1}	15
q_{i2}	10
$\tilde{q}_j$	20

Table A.4: Production and Assembly Costs

Parameter	$ per unit per month (SM)	$ per unit per day (OM)
h_{i1}	0.19	0.01
h_{i2}	0.13	0.01
$\tilde{h}_{j1}$	1.89	0.07
$\tilde{h}_{j2}$	1.89	0.07
$\tilde{h}_j$	0.84	0.03
p_s	-	0.02

Table A.5: Holding Costs and Pipeline Costs for Sub-assemblies and Final Products

A.3 Revenue Data

The tables below display the transfer prices charged by plant i to DC j, selling prices charged by DC j to customer k, and the tax and discount rates for each country.

	s	
	1	**2**
τ_{ijs}	20	15

Table A.6: Transfer Prices in $ per unit

	$ per unit
ρ_k	200

Table A.7: Selling Price of Final Product

Parameter	**Annual Rate**
TAX_c	0.25
r_c	0.05

Table A.8: Income Tax and Discount Rates

A.4 Lead Times

The lead time when traveling by air is equal to 1 day for all origin-destination pairs.

From/To	Tac	Reg	Win	Osh	Hal	Kan	Lex	ElP	Shr	Jac	Gui	Str	Gen	Rot	Emd
Mont	7	9	8	6	8	8	8	5	4	4	15	16	16	16	16
Rege	15	16	15	12	10	16	16	17	15	14	3	3	2	2	2
Hluk	15	16	16	12	10	17	17	17	16	14	4	3	3	3	2
Tych	15	17	16	12	11	17	17	18	16	14	4	3	3	3	3
Wars	14	16	15	12	10	16	16	17	16	14	4	3	3	3	2
Nitr	15	17	16	12	11	17	17	18	16	14	4	3	3	3	2
Gyor	15	17	16	12	11	17	17	18	16	14	4	3	3	3	2
Camp	17	18	17	14	12	18	18	19	18	16	5	4	4	4	4
Ista	16	18	17	14	12	18	18	19	18	16	4	4	4	4	4

Table A.9: Ocean Lead Times (in days)

From/To	Tac	Reg	Win	Osh	Hal	Kan	Lex	ElP	Shr	Jac	Gui	Str	Gen	Rot	Emd
Mont	9	8	7	8	11	4	6	3	3	5	-	-	-	-	-
Rege	-	-	-	-	-	-	-	-	-	-	2	1	1	1	1
Hluk	-	-	-	-	-	-	-	-	-	-	2	2	1	1	1
Tych	-	-	-	-	-	-	-	-	-	-	2	2	1	1	1
Wars	-	-	-	-	-	-	-	-	-	-	2	2	1	1	1
Nitr	-	-	-	-	-	-	-	-	-	-	2	1	2	2	1
Gyor	-	-	-	-	-	-	-	-	-	-	2	1	2	2	1
Camp	-	-	-	-	-	-	-	-	-	-	3	2	2	2	2
Ista	-	-	-	-	-	-	-	-	-	-	3	3	3	4	3

Table A.10: Rail Lead Times (in days)

From/To	Tac	Reg	Win	Osh	Hal	Kan	Lex	ElP	Shr	Jac	Gui	Str	Gen	Rot	Emd
Mont	7	6	5	6	8	3	4	2	2	4	-	-	-	-	-
Rege	-	-	-	-	-	-	-	-	-	-	3	1	2	2	2
Hluk	-	-	-	-	-	-	-	-	-	-	3	2	2	3	2
Tych	-	-	-	-	-	-	-	-	-	-	4	2	2	3	2
Wars	-	-	-	-	-	-	-	-	-	-	4	3	3	3	2
Nitr	-	-	-	-	-	-	-	-	-	-	3	2	2	3	2
Gyor	-	-	-	-	-	-	-	-	-	-	3	2	2	3	2
Camp	-	-	-	-	-	-	-	-	-	-	5	3	4	4	4
Ista	-	-	-	-	-	-	-	-	-	-	6	5	5	5	5

Table A.11: Truck Lead Times (in days)

A.5 Transportation Costs

A.5.1 From Plants to DCs

From/To	Tac	Reg	Win	Osh	Hal	Kan	Lex	ElP	Shr	Jac	Gui	Str	Gen	Rot	Emd
Mont	0.43	0.71	0.62	0.37	0.47	0.57	0.57	0.79	0.68	0.26	0.67	0.67	0.67	0.67	0.67
Rege	0.72	1.14	1.06	0.73	0.64	1.12	1.12	0.92	0.81	0.86	0.65	0.65	0.65	0.65	0.65
Hluk	0.76	1.18	1.09	0.77	0.67	1.15	1.15	0.95	0.85	0.89	0.68	0.68	0.68	0.68	0.68
Tych	0.70	1.17	1.08	0.76	0.67	0.98	0.98	0.89	0.78	0.70	0.62	0.62	0.62	0.62	0.62
Wars	0.66	1.13	1.04	0.72	0.63	0.95	0.95	0.86	0.75	0.66	0.58	0.58	0.58	0.58	0.58
Nitr	0.78	0.83	0.83	0.79	0.69	0.89	0.89	0.78	0.78	0.92	0.70	0.70	0.70	0.70	0.70
Gyor	0.78	1.20	1.11	0.79	0.69	1.17	1.17	0.97	0.87	0.91	0.70	0.70	0.70	0.70	0.70
Camp	0.67	1.04	0.95	0.67	0.76	0.96	0.96	0.86	0.76	0.67	0.32	0.59	0.27	0.27	0.26
Ista	0.61	0.98	0.89	0.61	0.72	0.89	0.89	0.80	0.69	0.61	0.23	0.20	0.23	0.23	0.22

Table A.12: Ocean Costs from Plant to DC (in $ per unit)

From/To	Tac	Reg	Win	Osh	Hal	Kan	Lex	ElP	Shr	Jac
Mont	5.84	5.23	5.09	5.13	7.33	2.99	3.90	1.72	1.83	3.50
Rege	15.99	14.10	13.51	12.53	10.45	14.87	13.76	17.34	15.82	14.72
Hluk	16.22	14.44	13.90	13.08	11.08	15.37	14.33	17.80	16.38	15.36
Tych	16.06	14.33	13.82	13.10	11.15	15.35	14.35	17.76	16.39	15.43
Wars	15.85	14.18	13.70	13.08	11.19	15.29	14.33	17.67	16.36	15.47
Nitr	16.38	14.37	14.03	13.17	11.14	15.48	14.41	17.92	16.47	15.42
Gyor	16.65	14.87	14.34	13.50	11.47	15.80	14.74	18.23	16.79	15.75
Camp	17.59	15.91	15.41	14.64	12.63	16.92	15.89	19.34	17.94	16.91
Ista	18.44	16.77	16.27	15.46	13.42	17.76	16.71	20.19	18.76	17.68

(a) To NAFTA DCs

From/To	Gui	Str	Gen	Rot	Emd
Mont	15.91	17.14	16.50	16.42	16.60
Rege	2.04	0.58	1.16	1.25	1.23
Hluk	2.82	1.37	1.81	1.84	1.61
Tych	3.06	1.63	1.96	1.96	1.65
Wars	3.31	1.94	2.16	2.13	1.75
Nitr	2.80	1.34	1.84	1.89	1.72
Gyor	3.11	1.65	2.17	2.22	2.04
Camp	4.22	2.79	3.33	3.38	3.17
Ista	4.90	3.52	4.11	4.18	4.00

(b) To EU DCs

Table A.13: Air Costs from Plant to DC (in $ per unit)

From/To	Tac	Reg	Win	Osh	Hal	Kan	Lex	ElP	Shr	Jac	Gui	Str	Gen	Rot	Emd
Mont	0.19	0.19	0.19	0.19	0.24	0.06	0.14	0.11	0.10	0.13	-	-	-	-	-
Rege	-	-	-	-	-	-	-	-	-	-	0.07	0.06	0.05	0.05	0.03
Hluk	-	-	-	-	-	-	-	-	-	-	0.10	0.10	0.07	0.07	0.06
Tych	-	-	-	-	-	-	-	-	-	-	0.10	0.10	0.08	0.07	0.06
Wars	-	-	-	-	-	-	-	-	-	-	0.12	0.12	0.09	0.09	0.08
Nitr	-	-	-	-	-	-	-	-	-	-	0.11	0.06	0.08	0.12	0.06
Gyor	-	-	-	-	-	-	-	-	-	-	0.11	0.07	0.08	0.08	0.07
Camp	-	-	-	-	-	-	-	-	-	-	0.14	0.11	0.13	0.11	0.14
Ista	-	-	-	-	-	-	-	-	-	-	0.12	0.10	0.13	0.15	0.11

Table A.14: Rail Costs from Plant to DC (in $ per unit)

From/To	Tac	Reg	Win	Osh	Hal	Kan	Lex	ElP	Shr	Jac	Gui	Str	Gen	Rot	Emd
Mont	0.59	0.51	0.45	0.51	0.72	0.26	0.35	0.17	0.16	0.32	-	-	-	-	-
Rege	-	-	-	-	-	-	-	-	-	-	0.21	0.08	0.11	0.13	0.14
Hluk	-	-	-	-	-	-	-	-	-	-	0.28	0.15	0.19	0.21	0.17
Tych	-	-	-	-	-	-	-	-	-	-	0.31	0.18	0.20	0.20	0.17
Wars	-	-	-	-	-	-	-	-	-	-	0.33	0.22	0.21	0.21	0.18
Nitr	-	-	-	-	-	-	-	-	-	-	0.30	0.17	0.20	0.23	0.20
Gyor	-	-	-	-	-	-	-	-	-	-	0.29	0.16	0.19	0.22	0.19
Camp	-	-	-	-	-	-	-	-	-	-	0.42	0.29	0.33	0.35	0.33
Ista	-	-	-	-	-	-	-	-	-	-	0.53	0.40	0.43	0.45	0.43

Table A.15: Truck Costs from Plant to DC (in $ per unit)

A.5.2 From DCs to Customers

From/To	Van	Cal	Mil	Det	Tor	Mon	San	Dal	Wee	Han	Cer	Stu
Tac	0.53	0.68	0.61	0.32	0.34	0.38	0.53	0.39	0.61	0.72	0.61	0.72
Reg	0.70	0.85	0.98	0.90	0.90	0.90	0.72	0.98	1.01	1.14	1.01	1.14
Win	0.61	0.77	0.89	0.81	0.81	0.81	0.63	0.89	0.92	1.05	0.92	1.05
Osh	0.35	0.50	0.61	0.53	0.53	0.53	0.38	0.30	0.60	0.73	0.60	0.73
Hal	0.45	0.61	0.61	0.53	0.53	0.53	0.49	0.41	0.50	0.63	0.61	0.63
Kan	0.69	0.85	0.89	0.81	0.81	0.81	0.68	0.89	0.98	1.11	0.97	1.11
Lex	0.41	0.56	0.61	0.53	0.53	0.53	0.39	0.60	0.69	0.82	0.69	0.82
ElP	0.33	0.49	0.61	0.53	0.22	0.27	0.28	0.60	0.61	0.72	0.61	0.72
Shr	0.45	0.60	0.69	0.62	0.62	0.32	0.41	0.69	0.69	0.81	0.69	0.81
Jac	0.41	0.57	0.61	0.53	0.53	0.53	0.39	0.60	0.72	0.85	0.71	0.85
Gui	0.61	0.76	0.67	0.61	0.58	0.53	0.61	0.68	0.53	0.64	0.53	0.64
Str	0.61	0.76	0.60	0.67	0.64	0.59	0.61	0.68	0.53	0.64	0.53	0.64
Gen	0.61	0.76	0.61	0.64	0.61	0.56	0.61	0.68	0.53	0.64	0.53	0.64
Rot	0.61	0.76	0.61	0.64	0.60	0.56	0.61	0.68	0.53	0.64	0.53	0.64
Emd	0.61	0.76	0.58	0.64	0.61	0.57	0.61	0.68	0.53	0.64	0.53	0.64

Table A.16: Ocean Costs from DC to Customer (in $ per unit)

From/To	Van	Cal	Mil	Det	Tor	Mon	San	Dal	Wee	Han	Cer	Stu
Tac	0.39	1.37	5.13	5.84	6.24	6.96	2.07	5.07	14.79	15.11	15.18	15.75
Reg	2.52	1.25	2.87	3.52	3.83	4.48	3.78	3.89	12.86	13.25	13.16	13.82
Win	3.52	2.25	1.99	2.58	2.84	3.47	4.57	3.58	12.26	12.69	12.51	13.21
Osh	6.31	5.08	1.28	0.65	0.14	1.01	6.85	3.63	11.30	11.84	11.36	12.19
Hal	8.38	7.09	3.70	3.06	2.43	1.48	9.22	6.11	9.27	9.85	9.22	10.10
Kan	4.72	3.76	1.33	1.91	2.54	3.54	4.54	1.41	13.63	14.13	13.75	14.54
Lex	6.10	4.99	0.97	0.70	1.26	2.21	6.17	2.45	12.54	13.08	12.58	13.42
ElP	4.50	4.22	3.85	4.41	5.05	6.06	3.01	1.71	16.09	16.57	16.24	17.02
Shr	5.77	4.99	2.40	2.68	3.30	4.28	5.01	0.55	14.60	15.13	14.65	15.48
Jac	7.63	6.64	2.86	2.53	2.85	3.50	7.16	2.73	13.55	14.13	13.47	14.36
Gui	14.73	13.62	11.94	11.46	10.82	9.83	16.60	14.44	1.39	1.94	0.78	1.68
Str	15.41	14.38	13.08	12.65	12.02	11.04	17.43	15.63	0.88	0.87	0.71	0.22
Gen	14.71	13.68	12.42	12.00	11.37	10.40	16.73	14.97	0.24	0.73	0.53	0.83
Rot	14.58	13.55	12.33	11.93	11.30	10.33	16.60	14.89	0.09	0.69	0.67	0.94
Emd	14.51	13.52	12.48	12.12	11.48	10.53	16.59	15.43	0.41	0.37	1.13	1.04

Table A.17: Air Costs from DC to Customer (in $ per unit)

From/To	Van	Cal	Mil	Det	Tor	Mon	San	Dal	Wee	Han	Cer	Stu
Tac	0.03	0.09	0.13	0.03	0.18	0.19	0.07	0.14	-	-	-	-
Reg	0.08	0.05	0.11	0.13	0.11	0.12	0.14	0.13	-	-	-	-
Win	0.07	0.07	0.09	0.11	0.09	0.10	0.15	0.09	-	-	-	-
Osh	0.17	0.14	0.06	0.05	0.03	0.05	0.06	0.08	-	-	-	-
Hal	0.21	0.18	0.14	0.12	0.08	0.07	0.24	0.17	-	-	-	-
Kan	0.03	0.13	0.06	0.02	0.10	0.12	0.03	0.06	-	-	-	-
Lex	0.18	0.15	0.05	0.05	0.08	0.10	0.15	0.07	-	-	-	-
ElP	0.14	0.14	0.10	0.11	0.15	0.17	0.02	0.05	-	-	-	-
Shr	0.14	0.16	0.08	0.08	0.12	0.14	0.13	0.04	-	-	-	-
Jac	0.21	0.18	0.08	0.08	0.11	0.12	0.17	0.08	-	-	-	-
Gui	-	-	-	-	-	-	-	-	0.03	0.05	0.02	0.04
Str	-	-	-	-	-	-	-	-	0.04	0.05	0.03	0.03
Gen	-	-	-	-	-	-	-	-	0.02	0.03	0.03	0.04
Rot	-	-	-	-	-	-	-	-	0.01	0.03	0.03	0.04
Emd	-	-	-	-	-	-	-	-	0.03	0.01	0.05	0.05

Table A.18: Rail Costs from DC to Customer (in $ per unit)

From/To	Van	Cal	Mil	Det	Tor	Mon	San	Dal	Wee	Han	Cer	Stu
Tac	0.05	0.20	0.53	0.62	0.66	0.71	0.21	0.58	-	-	-	-
Reg	0.29	0.13	0.29	0.38	0.42	0.46	0.43	0.40	-	-	-	-
Win	0.38	0.22	0.22	0.31	0.34	0.38	0.50	0.35	-	-	-	-
Osh	0.69	0.54	0.14	0.08	0.02	0.09	0.70	0.39	-	-	-	-
Hal	0.29	0.23	0.13	0.11	0.09	0.07	0.29	0.19	-	-	-	-
Kan	0.53	0.41	0.16	0.21	0.27	0.35	0.48	0.15	-	-	-	-
Lex	0.68	0.52	0.13	0.10	0.16	0.25	0.63	0.24	-	-	-	-
ElP	0.49	0.48	0.42	0.47	0.53	0.62	0.32	0.18	-	-	-	-
Shr	0.66	0.54	0.26	0.29	0.36	0.44	0.51	0.06	-	-	-	-
Jac	0.82	0.70	0.30	0.27	0.31	0.34	0.74	0.28	-	-	-	-
Gui	-	-	-	-	-	-	-	-	0.15	0.20	0.08	0.17
Str	-	-	-	-	-	-	-	-	0.10	0.10	0.09	0.03
Gen	-	-	-	-	-	-	-	-	0.04	0.07	0.08	0.08
Rot	-	-	-	-	-	-	-	-	0.02	0.08	0.08	0.11
Emd	-	-	-	-	-	-	-	-	0.05	0.05	0.13	0.12

Table A.19: Truck Costs from DC to Customer (in $ per unit)

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