A Phased Approach to Distribution Network Optimization Given Incremental Supply Chain Change

by

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Submitted to the MIT Sloan School of Management and the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Engineering Systems

In conjunction with the Leaders for Global Operations Program at the Massachusetts Institute of Technology

June 2012
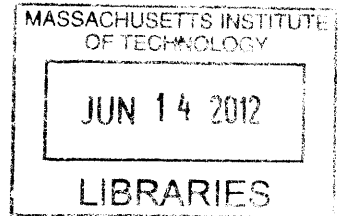
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Abstract

This thesis addresses the question of how to optimize a distribution network when the supply chain has undergone an incremental change. A case study is presented for Company A, a major global biotechnology company that recently acquired a new manufacturing facility in Ireland. Company A already has international operations throughout Europe and the rest of the world through its network of 3rd party logistics providers, wholesalers, and distributors, as well as its own Benelux-based international distribution center. It now seeks to optimize its current network by taking into consideration the possibility of distributing product directly out of Ireland and by potentially outsourcing some of the distribution currently sourced from its Benelux facility.

The thesis uses a phased approach to optimizing the network in order to tackle the common enterprise challenges of 1) building consensus around the solution and 2) simultaneously learning about the problem while attempting to solve it in order to meet a compressed project schedule. Through a number of simplifications, the thesis reduces the problem scope to a level that both enables the use of this phased approach and provides for a less-complex and less time-intense analysis manageable within the given time frame.

The unique characteristics of the biotechnology industry drive the analysis to closely study direct effects of and potential risks to availability and lead-time of the various distribution options while trading off distribution, packaging, inventory, and capital expenditure costs. The recommendations resulting from the analysis described in this thesis are used to inform Company A's future distribution strategy regarding additional warehousing capacities, the continued use of the Benelux facility, as well as potential strategic partnerships with 3rd party logistics service providers.

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Acknowledgments

First of all, I would like to give my thanks to my thesis advisors Don Rosenfield and Chris Caplice for their insights and recommendations on this project. Don, your dedication and contribution to the LGO program as well as your positive impact on the many students that have passed through the halls of E40 and E51 is felt every day. Chris, thank you for taking a leap of faith in supervising me. I also wish to acknowledge the Leaders for Global Operations Program for its support of this work.

Many co-workers at "Company A" were critical to this internship, which was both stimulating and enjoyable. Thank you Bill K for your invaluable advice and mentorship: I feel that had a unique opportunity to learn and grow through our close working relationship. Rayne, thank you for your continued support of the LGO program through your sponsorship of interesting and engaging internships. Leigh, I cannot imagine having gone through the internship process without you. Your assistance and guidance throughout my time at Company A made the experience as smooth as possible and provided both me and my fellow interns innumerable opportunities to learn and network. Thank you also to the rest of the team at headquarters: Majed, Leticia, Peter P, Chris A. Your expertise and company allowed me to not only succeed in my project, but also have an enjoyable experience. To the team at "Site D," I am indebted to you for sharing your knowledge and helping steer the project. Thank you Robert-Jan, Paul D., Peter Y, Jan B., Theo T., and the many other employees that I had the honor of working with.

Finally, I would like to thank my family. To my parents, Kathy and Klaus, I am grateful every day for the support and love that has allowed me to flourish. To my grandparents, Sally and Ernest, thank you for fostering a family that I can be proud of, that I enjoy spending time with, and that I will always know that I can rely on.

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Note on Proprietary Information

In order to protect proprietary information, data and figures for "Company A" have been modified to be illustrative of the problem, but exclude details that may be harmful if disclosed to the general public.

Chapter 1: Introduction

1.1 Project Background

The thesis project originated under the premise that adding new supply points to a supply chain merits reevaluating that supply chain. Shortly before initiating the project, Company A purchased a new manufacturing plant in Ireland (Site I). This facility was purchased as part of a larger risk mitigation strategy in order to provide backup capabilities for manufacturing and distribution and is intended to complement the existing manufacturing (Site M) and mainland Europe distribution (Site D) operations.

With the acquisition complete, Company A must make various decisions regarding the future use of this facility. The thesis project focuses on optimizing the logistics network of direct shipments to customers and bulk shipments to third party logistic service providers (3PLs) for the international market given the described incremental change to the existing supply chain.

In this thesis, we consider the distribution network's current and future capabilities, including the potential for warehouse expansion. Through comprehensive understanding and analysis of current distribution operations as well as of the impact of potential distribution network changes, we optimize the network over cost and risk while meeting service level and lead-time requirements. For these purposes, we consider the following distribution options: 1) continuing distribution through Site D, 2) distribution from Site I, 3) outsourcing distribution to a 3PL, and 4) a hybrid solution. A hybrid solution represents an optimization where some item demands are served from one site, while others are served from one or more other sites.

1.2 Problem Statement

The purpose of this thesis is to provide an analytical framework for making optimal distribution network decisions for an incremental change in the supply chain. This case study specifically evaluates an incremental change in a two-echelon supply chain for a high-value goods business with extremely stringent lead-time requirements. Furthermore, in order to reduce computational complexity and expedite decision-making, only the inter-country distribution is under discussion – modifying the in-country distribution chain is out of scope. For product previously manufactured at Site M and distributed from Site D, but now manufactured at Site I, what portion should be distributed directly from Site I, from Site D, or from a 3PL distribution site?

The immediate need for strategic decisions regarding an existing supply chain infrastructure necessitates a solution methodology that is collaborative, easily understood and communicated, and sufficiently flexible to incorporate new information gathered in parallel. Furthermore, since the problem is embedded into an existing, functioning, and critical supply chain, the solution approach must incorporate strategic, tactical, and operational decision-making processes in order to gain sufficient support from all levels of the supply chain organization.

The final solution must optimize the distribution network's net present value without compromising its ability to serve patients on time every time. This thesis demonstrates the benefits of applying a phased problem-solving approach to this type of issue and highlights many potential optimization variables.

1.3 Thesis Structure and Overview

The first section of this thesis is dedicated to providing background on the problem this thesis means to address, on Company A's operations and ecosystem, as well as on literature relevant to the problem under discussion. Chapter 1 grounds us in the motivation and problem addressed by this thesis. Chapter 2 provides background on Company A's operations and its current distribution and supplier network, a brief outline of the biotechnology production-distribution process, as well as an overview of the logistics landscape and challenges of distributing in Europe more broadly and Ireland more specifically. Chapter 3 presents literature on the major concepts surrounding the problem under discussion, including a variety of approaches to solving facility location problems, prior LGO theses performing cost and risk analyses, and why a company would decide to outsource their logistics to a 3rd party logistics provider.

The second section of this thesis addresses the methodology chosen to solve the network optimization problem. Chapter 4 provides a high-level overview of the methodology while contrasting the approach used to a more computational approach described in one of the literature references. Chapter 5 describes the demand segmentation and data-gathering phase from which we derive several analysis simplifications. Chapter 6 describes the process in which possible distribution solution options are generated and then filtered to a smaller set of options that can be manually compared with relative ease in the last phase. Chapter 7 describes that last phase of comparing options in order to find the optimal set of distribution sites and shipment modalities given the tradeoffs between distribution/packaging costs, labor costs, inventory costs, and capital expenditure.

The final section of this thesis is contained in Chapter 8, which summarizes some of the observations made over the course of the project, comments on the efficacy of the methodology used, and provides some suggestions on further research to augment the existing project analysis.

Chapter 2: Background

2.1 Company A

Company A is a large global biotechnology company with operations mainly in the United States and Europe. The company manufactures close to ten different drug substances that are sold worldwide, translating into thousands of individual drug product stock keeping units ("SKUs") differentiated not only by drug substance type, concentration, and volume, but also by language, drug delivery mechanism (vial, syringe, etc.), and quantity. Although the company has several small-molecule drugs currently in development and being manufactured, it focuses mainly in the development and manufacture of large-molecule drugs through the biotechnology production process for which it utilizes both in-house and contract manufacturing resources.

The company uses both in-house and outsourced resources for manufacturing and distribution, with most manufacturing located in the United States and international distribution mainly sourced from mainland Europe. Figure 1 provides an illustrative map of Company A's sites.

Figure 1 - Illustrative Map of Company A's Sites
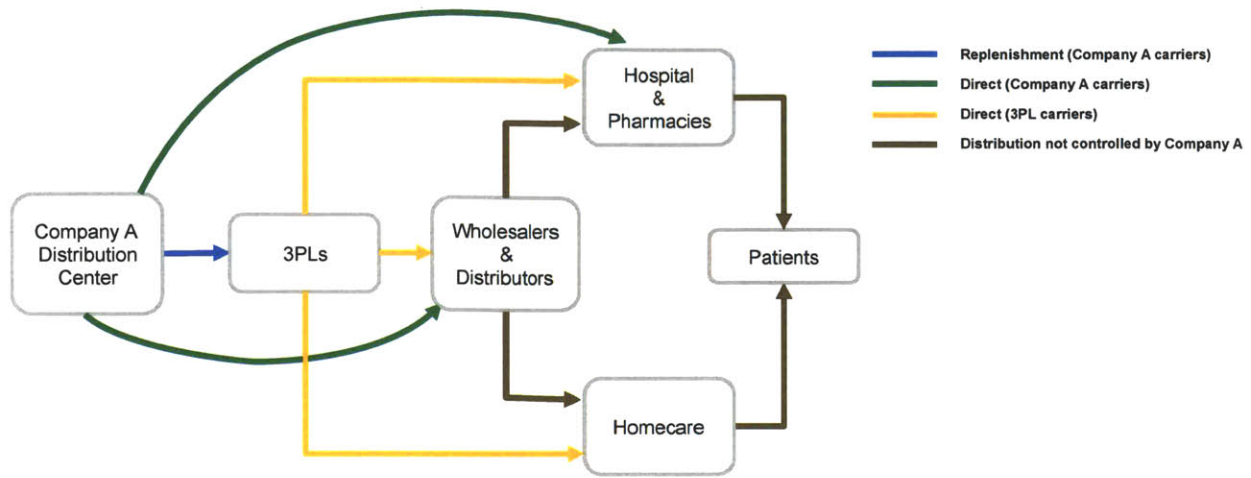
Figure 2 - Company A Distribution Network Flows

Figure 2 shows a generalized flow diagram for these mechanisms, while Figure 3 provides geographical context for the current state of distribution flows. The product, after manufacture, is initially stored in Company A's distribution center. From there, various paths are used to deliver the product to the patient.
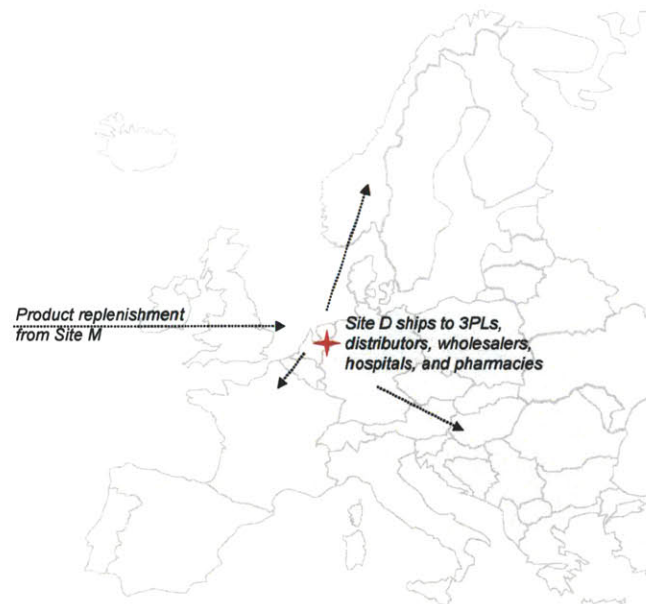
Figure 3 - Illustrative Map of Current International Distribution Flows

Hospitals, pharmacies, and homecare providers are each equipped to directly interface with the patient. All three entities generally carry little or no inventory. This means that very fast, generally 1-day, order-to-delivery windows (henceforth called "lead times") are necessary to service these entities. Furthermore, shipment sizes are often small, ranging from one to tens of packs.

Four types of companies participate in Company A's distribution network, each assuming different levels of responsibility and requiring different levels of support. These are elaborated in Figure 4 below.

Type of company	Role/Responsibility	Relationship to Company A	Current Level of Support
Company A Distribution Center	Hold inventory and manage distribution to rest of distribution network	Owned	Periodic bulk replenishment shipment from Site M with timing determined by manufacturing schedule and demand
Third-party logistics (3PL) provider	Performs logistics functions such as warehousing, order processing, pick/pack, and distribution to customers. Does not take title to product	Contracted; Company A has full insight into inventory and controls shipment activity	Periodic bulk replenishment shipments from Site D with urgency determined by Company A
Distributor	Perform sales and marketing activities in territory. Responsible for legal or regulatory compliance. Assumes title to product and resells to customers (wholesalers, pharmacies, hospitals, homecare)	Customer	Periodic bulk replenishment shipments from Site D with pre-negotiated schedule and speed
Wholesalers	Do not perform sales and marketing activities. Not responsible for legal or regulatory compliance. Assumes title to product and resells to customers (pharmacies, hospitals, homecare)	Customer	Periodic bulk replenishment shipments from Site D with pre-negotiated schedule and speed

Figure 4 - Entities in Company A's Distribution Network

Company A uses a different combination of distribution methods for each country, each uniquely suited to the market demands and requirements. The chosen distribution model depends on variety of factors, including lead time requirements, total country demand, country-by-country regulatory requirements, Company A's familiarity with the market (first entry strategy is often via distributor), implementation cost, risk (using an in-country entity is less risky), and control (a Company A-owned DC or a Company A-controlled 3PL provides a higher level of control than the use of a distributor or wholesaler).

2.2 Biotechnology Production-Distribution Overview

The biotechnology production process is generally defined by the *bulk manufacturing, formulation and fill, labeling, inspection,* and *packaging* steps. After production, the product is ready for *distribution* to patients.

The *bulk manufacturing* step produces the pharmaceutical active ingredient through a biological process. In this process, a cell is genetically engineered to produce the desired pharmacologically active protein – the active ingredient. In order to produce sufficient volumes of that protein, the cell must be replicated millions of times. These quantities are achieved by a scale-up procedure whereby ideal conditions for cell replication are created and monitored in progressively larger vessels until the final stage, which uses a production vessel – generally 1000+ liter containers – to facilitate optimal growth conditions on a larger scale. After sufficient quantity of cells has been produced over a period of 32-40 days, the proteins must be extracted from the solution and purified through a series of filtration and chromatography steps. The bulk manufacturing process results in outputs of carboys or cryovessels of bulk "drug substance" ("DS").

The *formulation and fill* process consists of stabilizing and diluting the bulk drug substance to the appropriate concentration before filling the solution into vials or syringes, resulting in drug product ("DP"). Typically, the drug product *inspection* immediately follows. However, if a given drug product is designated for distribution in Europe, European Union (EU) restrictions require that drug product inspections must take place in the EU.

At this point, the inspected drug product ("IDP") is ready for *packaging*. This is sometimes called the *finish* step. Multiple packaging configurations may be used depending on the product and market and can include 1-pack or multi-pack configurations, top-load and side-load, and may be labeled in a variety of languages. This is the main differentiating step and is therefore postponed where possible. The packaging step results in the finished drug product ("FDP"). It is interesting to note that especially in the

biopharmaceutical industry, it often makes sense to hold large inventory stockpiles in later stages of production. This is due to a variety of reasons, including supply and demand uncertainty, long production and inspection cycles, very high sales value relative to cost of goods sold ("COGS"), multiple year product longevity, and the fact that supplying a patient with life-saving medicine is generally more important than reducing inventory holding costs.

In the FDP stage, the product is ready for *distribution* to be used by patients around the world. Most biopharmaceutical products require "cold chain" distribution, whereby the product is kept at a constant low temperature to maintain its pharmaceutical properties. Furthermore, in order to maintain regulatory compliance, safeguards and monitoring methods to prove temperature regulation must be in place throughout the product lifecycle. Some of these methods include use of temperature-monitoring devices, specially designed insulated packaging materials rated for the duration of time expected for shipment, time stamps in and out of refrigerated storage, and shipment via actively-refrigerated trucks. These cold chain challenges and other challenges must all be surmounted throughout the pharmaceutical industry distribution network.

2.3   Logistics in Europe and Ireland

Like many other companies, Company A recognized that the life sciences industry in Ireland is thriving through significant governmental support, including a variety of tax incentives. A host of other biotechnology, small molecule pharmaceutical, medical device, and nutritional goods manufacturers have all established themselves on the island [1]. As a result, when it was given the opportunity, Company A decided to purchase an additional manufacturing plant on Ireland for risk-mitigation purposes. Given that Company A's international distribution currently originates in Europe and is now being considered from Ireland, a brief overview of logistics for Europe and Ireland will be provided.

The European logistics environment provides an interesting challenge to the supply chain designer. Its large cultural and language diversity within a relatively small geographic area coupled with recent economic, political, and regulatory developments creates a complex and rapidly changing setting that demands a great deal of foresight and flexibility in creating a supply chain strategy. The recent trend to remove or reduce trade barriers has enabled freer access to markets. Where only 20 years ago inter-country logistics systems were arduous to implement, now such inter-country logistics integration and resource streamlining has become viable. While the ease of crossing state borders in the United States has not yet been achieved, the European Union is continually working to move their member countries in that direction. Players in the European logistics market must take these trends into account.

Depending on the size of the distributing company, its demand profile, product lead time requirements, and a host of other variables, a given company might consider using one of three distribution structures: a local, regionalized, or centralized distribution structure using a European DC. The industry trend in Europe is towards consolidation and globalization, which is driving many companies towards a centralized structure, while the growing importance of Eastern European demand is increasing opportunities for eastern regional DCs [2].
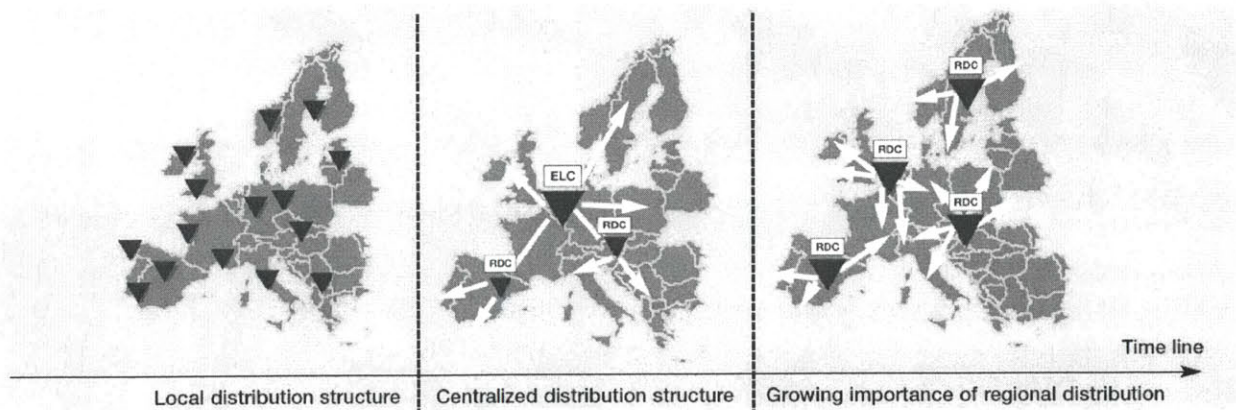

Figure 5 - Evolution of Distribution Structures Over Time[1]

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[1] Figure excerpted from [2]

The Benelux countries (Belgium, Netherlands, and Luxembourg), France, and Germany remain popular locations for pan-European distribution centers for the pharmaceutical industry and many other industries due to their good infrastructure and tendency to be located at the demand center of gravity. Throughout Europe, road freight remains the principal mode of transport [3]. Despite good road, rail, sea, and airfreight infrastructure, shipping within as well as out of Europe is still relatively difficult when compared with domestic, in-country shipments. Especially at the fringes of the European Union, that infrastructure is a patchwork of national networks whose structures are intimately linked with a variety of geographic, economic, political, and historic factors. The characterization by O'Laughlin (1993) of individual countries' network structures in terms of their level of infrastructure development and their physical shape, whether net-shaped (decentralized) or star-shaped (centralized), while somewhat outdated, remains germane in most cases. [4] It is generally easier to implement inter-country distribution for countries with net-shaped transportation networks, such as found in the Benelux countries, while countries such as Spain that have maintained star-shaped networks present difficulties. In order to reach the extremities of such countries, a circuitous path via the star's central node must be taken which can add substantial and even unacceptable delays.

Another aspect of distributing within Europe is the presence of many regulations that impact shippers' service levels, availability of transport modes, shipping times, and transportation costs. Further regulations designed to protect the health and safety of the general public impact the sale and distribution of pharmaceuticals [4]. In sum, these regulations add a lot of complexity to the distribution process – especially when shipping outside of the European Union [5].

Distributing from an island, such as from Ireland, brings further complexities. It is no longer possible to use road freight as the sole mode of transport. Instead, that modality must be combined with either sea or air modes of transport. Two sea modalities exist: roll-on roll-off ("RoRo") and lift-on lift-off ("LoLo"). The so-called RoRo modality is what is commonly referred to as a ferry. It allows trucks to drive directly on to and off of the ship with its freight. This results in reasonably fast turnaround times, and low amount

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of extra cargo handling. The LoLo modality is commonly referred to as a container ship. In this modality, cranes lift intermodal containers directly off of trucks and onto the ship. This results in longer turnaround times – often depending significantly on the capabilities of the particular seaport – and more cargo handling complexity. However, given the larger number of containers that can fit on any given container ship compared with the number of trucks that fit onto a given ferry, this modality is generally less expensive and more appropriate when used for longer shipping distances and low-urgency freight. Finally, airfreight may be used to ship goods off of an island. This modality is fastest for longer distances, but is significantly more expensive than either sea modality [6].

O'Laughlin provides a succinct summary of the challenge faced by Company A in this project: "Evaluating the total cost and service tradeoffs in integrated pan-European logistics networks requires logistics network strategy models which can simultaneously consider the combined effects of inventory, warehousing, and transportation costs, as well as desired levels of customer service." [4] This thesis provides a framework to address not only the complexities generated by operating within a large part of Europe, but also those generated by distributing out of Ireland.

Chapter 3: Literature Review

High-value, innovative products such as Company A's biopharmaceutical products require a responsive supply chain able to prevent both stock-outs and supply disruptions. A responsive supply chain ensures the company's ability to serve patient needs at all times, even when faced with high demand uncertainty. Per Fisher (1997), this responsiveness can be achieved by a variety of means, including reducing lead times, increasing safety stock buffers, choosing high-quality, fast, and flexible suppliers, and delaying product differentiation [7]. Assuming the product manufacturing process is predefined, as in this case study, the optimal responsive distribution network will reduce cost and risk while keeping lead times low and safety stock buffers high.

This analysis also evaluates the potential use of 3PL partners in designing the most efficient supply chain. In order to fully explore the potential tools and methods to evaluate this problem, a range of literature was examined including facility location problem literature, other Leaders for Global Operations theses that analyze both supply chain cost and risk, and 3PL selection frameworks.

3.1   Facility Location Problems

A variety of facility location problems (FLPs) exist, each with many potential solution methodologies. Klose and Drexel (2005) provide a taxonomy of models to solve these FLPs, broken down into continuous and discrete methodologies [8]. The former method is best suited to place new construction sites for so-called "greenfield" sites while the latter facilitates decisions between existing site options.

Continuous FLPs are one way of computing the ideal location for one or more greenfield sites from a continuous solution space. This method typically minimizes or maximizes an objective function defined by some combination of distances, capital, labor, distribution, tax, and other costs given a set of supply and demand points. When evaluating proposed greenfield facility locations, such as those resulting from a

continuous FLP solution, Mentzer (2008) recommends reviewing seven different key site selection considerations: availability of sufficient land, cost-effective access to labor, easy access to sufficient capital, proximity to supply, expected production activities at site, proximity to demand, and adequate access to logistics facilities [9].

Alternatively, existing site location possibilities may be evaluated using discrete FLPs. Earlier works in this field include Geoffrion and Graves' (1974) seminal work on multi-commodity distribution system design [10] and Erlenkotter's (1978) approach based on linear programming [11]. Both works use mixed-integer programming techniques to determine the placement of distribution centers, taking into account startup and distribution costs. Later works have highlighted the need for more complete analyses, whether through application of stochastic parameters in highly uncertain demand scenarios [12], using multi-period planning horizons to take into account the possibility of future capacity expansion [13], or taking into account tactical and operational considerations such as decisions about inventory stock [14], transportation modes [15], etc.

Melo, Nickel, and Saldanhadagama (2009) establish a taxonomy of discrete FLPs, which are defined by various characteristics: 1) uncapacitated vs. capacitated, 2) single-period vs. multi-period planning horizon, 3) deterministic vs. stochastic parameters (e.g. demands and costs), 4) single-commodity vs. multi-commodity, 5) single-echelon vs. multi-echelon, and 6) solely strategic vs. strategic, tactical, and/or operational. These problems may use a variety of supply chain performance measures including cost, profit, or multi-objective functions and be solved by a specific algorithm or general solver to reach either an exact or a heuristic solution [16].

Using these criteria, we may define Company A's problem as an uncapacitated, single-period, deterministic, single-commodity, two-echelon (See Figure 6) facility location problem that also must take into consideration tactical decisions such as 1) inventory allocation since the potential for warehouse expansion must be evaluated, 2) transportation modes given the unique challenges of transporting goods

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from an island, and 3) the unavoidable lead time requirements necessary to adequately serve patients. We may assume that both goods transport and warehouse size are uncapacitated since Company A outsources its goods transport to scalable 3rd parties and since we consider the opportunity to expand existing warehouse sizes, in particular at Site I. For the purposes of this project, only a single planning period is in scope – no future expansion is considered. Similarly, we assume both deterministic demand and costs due to relative historical stability and in order to expedite the analysis. As will be discussed later in this thesis, while several categories of products are distributed via multiple modalities, the deciding factor on the lane and modality used is not the product SKU, but rather the differing customer requirements for any SKU. Furthermore, we show that it is always best to serve all SKUs for given country from a single site rather than serving some SKUs for a given country from one site and some from another. This enables a modified single-commodity analysis. Finally, this is a two-echelon problem with a single-echelon location decision: while the product supply is fixed at Site I, there are multiple distribution site options, including from the upper layer of product supply. With these characteristics defined, we explore an example of this class of problem in further detail.
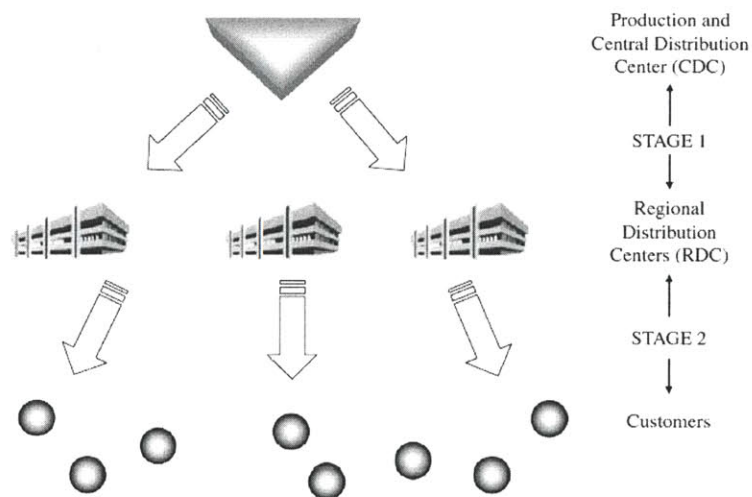

Production and
Central Distribution
Center (CDC)

STAGE 1

Regional
Distribution
Centers (RDC)

STAGE 2

Customers

Figure 6 - A Two-Stage Distribution System [2]

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[2] Figure excerpted from [28]

Sadjady and Davoudpour (2011) present a sophisticated model of this type. They use a mixed-integer linear program ("MILP") to minimize a total cost objective function for a two-echelon, multi-commodity supply chain network design with mode selection, lead times, and inventory costs. The mathematical formulation accounts for fixed and variable costs of opening and operating facilities and both shipping and holding product, as well as for incremental lead time cost (See full formulation in Appendix 1: Sadjady and Davoudpour's Problem Formulation). Furthermore, it models demand, warehouse and plant capacity levels, lead times, and service frequency from plant to warehouse and from warehouse to retailer. Its four decision variable categories include 1) the fraction of a given retailers demand for a given product delivered from a given warehouse via a given transportation mode, 2) the fraction of a given warehouse demand for a given product delivered from a given plant via a given transportation mode, 3) a binary variable for a given warehouse to open with a given capacity, and 4) a binary variable for a given plant to open with a given capacity. Through a Lagrangian relaxation, they develop a heuristic solution algorithm to find near-optimal solutions in reasonable computation time [17].

Other works have highlighted the practical need for alternative, more holistic methods of analysis. Camm and Chorman (1997) combine multi-phase modeling approaches and a graphical information system to improve intra-company collaboration and speed up company decision-making [18]. Tuominenb (1996) uses an Analytic Hierarchy Process ("AHP") decision aid to evaluate tangible quantitative and intangible qualitative criteria [19]. Smith (2003) describes how using integrated spreadsheet modeling for supply chain analysis enables flexibility and communicability that are extremely valuable when approaching poorly understood and/or evolving problems [20]. As suggested by these holistic methods of analysis, the solution methodology in this thesis recognizes the need for quantitative and qualitative analysis, for flexibility, and for communicability and performs analyses with the analytical rigor that such a strategic issue deserves.

3.2 Cost and Risk Analyses

Two recent theses capture the current corporate trend to pursue strategies that reduce both cost and risk. Similar to this project for Company A, Constantine (2009) and Feller (2008) assess both of these factors in their project solutions.

Constantine evaluates a U.S.-based engineered-goods manufacturer options for international manufacturing and distribution capacity expansion. Two major drivers for this project are the company's desire to increase its international sales and to address tariff and other trade barriers in certain markets. She approaches the problem with a three-pronged approach: 1) a simplified cost model to analyze material and inventory flows to a single international site, 2) a regional extension to the single-site cost model to evaluate a given site's ability to serve entire regions, and 3) a qualitative risk factor evaluation for each potential site. The cost models take into manufacturing (materials, conversion, kitting/consolidation), transportation, tax and tariff, and inventory costs. Constantine's risk factor evaluation consists of creating a site selection matrix that both evaluates each site on a given risk factor and weights the relative importance of risk factors with weightings calculated by the author's qualitative assessment of each factor's impact. This enables sites to be compared against one another using a weighted average score calculated by the sum of each site's weighted performance [21].

Feller assumes a similar approach to enable strategic sourcing decision-making for the medical device company, PerkinElmer. He creates a supplier evaluation tool for all global manufacturing sites that evaluates both total landed cost and risk-adjusted cost. Similar to Constantine, Feller's total landed cost takes into account transportation, tax and tariffs, and inventory costs. Furthermore, he includes purchasing and financing costs in his model since the tool evaluates external suppliers. The supplier risk assessment, unlike in Constantine's discrete approach, is then embedded into the cost numbers through risk-adjustment factors. A Failure Mode Effects Analysis (FMEA) technique is used to generate scores for different risk factors based on severity, probability of occurrence, and likelihood of detection. Those risk factors are categorized to match various cost categories (e.g. the logistics/trade compliance risk category

matches the freight cost category). Then, by calculating risk-adjustment factors for these categories, the model can multiply the cost by its matching risk-adjustment factor to find the risk-adjusted cost [22].

It should be noted that, unlike the project detailed in this thesis for which the need was both specific and urgent, both projects outlined above provided tools to be used more generically for multiple possible sites or suppliers at some point in the future. The impact of this difference will be discussed in the body of this thesis.

3.3   3PL Selection

With the option of outsourcing a portion of distribution to one or more 3PLs under consideration, we also examine literature on 3PL selection. Academic research on the 3PL industry is relatively new, with 3PL utilization having become common only in the last two decades. Capgemini's annual 3PL study shows that operating companies are increasing use of 3PLs instead of in-house distribution resources. Furthermore, companies are trying to consolidate the number of 3PLs used.

Per the 2012 study, the perceived benefits of using 3PLs include logistics cost and fixed-asset reduction, inventory cost reduction, reduced average order cycle length, and improved order fill rate and accuracy. However, companies may have reservations about using 3PLs if logistics is already a core competency of firm, there are no expected cost reductions, fears exist about reduced control, if the company expects reduced service levels or has IT system or security concerns [23].

Anderson, Coltman, Devinney, and Keating (2011) complement this study by assessing the relative importance of seven key service attributes in 3PL provider choice by a statistical analysis of 998 Asia-Pacific companies. They find that there are three segments of firms with varying decision-making criteria. The first segment, comprising 62% of responding companies, most values reliable performance, customer interaction, and customer service recovery. Notably, neither high or poor performance is greatly rewarded or penalized by this segment. Furthermore, these companies are relatively price insensitive. The second segment, comprising 27% of responding companies, most value reliable performance and are sensitive to price. The third and final segment is primarily concerned with price [24].

The idea that company type is a determining factor in criteria used to choose 3PL providers finds a counterpoint in Marasco's (2008) work. Her work suggests that 3PL selection takes place within a given context of internal factors such as the company size, structure, strategies that might define the three company segments in the previously-referenced work, as well as external factors such as economic trends, regulatory (or deregulation), and technology (just-in-time, computers) developments. In addition to

discussing potential factors determining 3PL choice, she summarizes several factors determining successful relationships between 3PL providers and their customers. Per her research, long-term, partnership-like relationships have the best success, which result in reduced cost, better service levels and customer satisfaction [25].

As suggested in the literature, we see that Company A is following the industry trend by considering additional use of 3PL to complement and potential replace some portions of its distribution network capabilities. While Company A's exact classification within one of Anderson, Coltman, Devinney, and Keating's (2011) segments may elude us, Marasco's findings that both internal and external factors frame a company's choice of 3PL provider do hold true and will be discussed further later in this thesis.

Chapter 4: Methodology Overview

In principle, the project seeks to optimize the distribution flow of every item from sources to markets over cost while maintaining or improving the customer lead-times and practically eliminating the possibility for supply disruption. This, as discussed in the literature review, is very similar to the formulation treated by Sadjady and Davoudpour ("S&D"), which can been viewed in full in Appendix 1. However, we find that various particularities of the problem both enable and require a modified, more manual phased approach using the same principles. First, we have a limited solution space enabled by the incremental network change. This allows for a manual, rather than automated solution method. Second, the combination of our team's limited prior knowledge of the problem, our short project time frame, and the fact that this high-sensitivity project requires periodic project reviews and alignment together called for a method that enables on-the-fly learning, in-progress communication, and manual intervention.

The applied problem-solving methodology consists of three phases that roughly correspond with understanding the current state, brainstorming and narrowing down potential solutions, and thoroughly evaluating potential solutions to find the optimal solution. For a distribution network-related problem such as this one, those phases consist of 1) segmenting the demand in accordance with a variety of distribution-related criteria, 2) generating distribution options that could potentially satisfy the demand segments from Phase 1 and then eliminating options that do not make sense, and 3) evaluating the remaining options using a total cost analysis. These phases are depicted in Figure 7 below.

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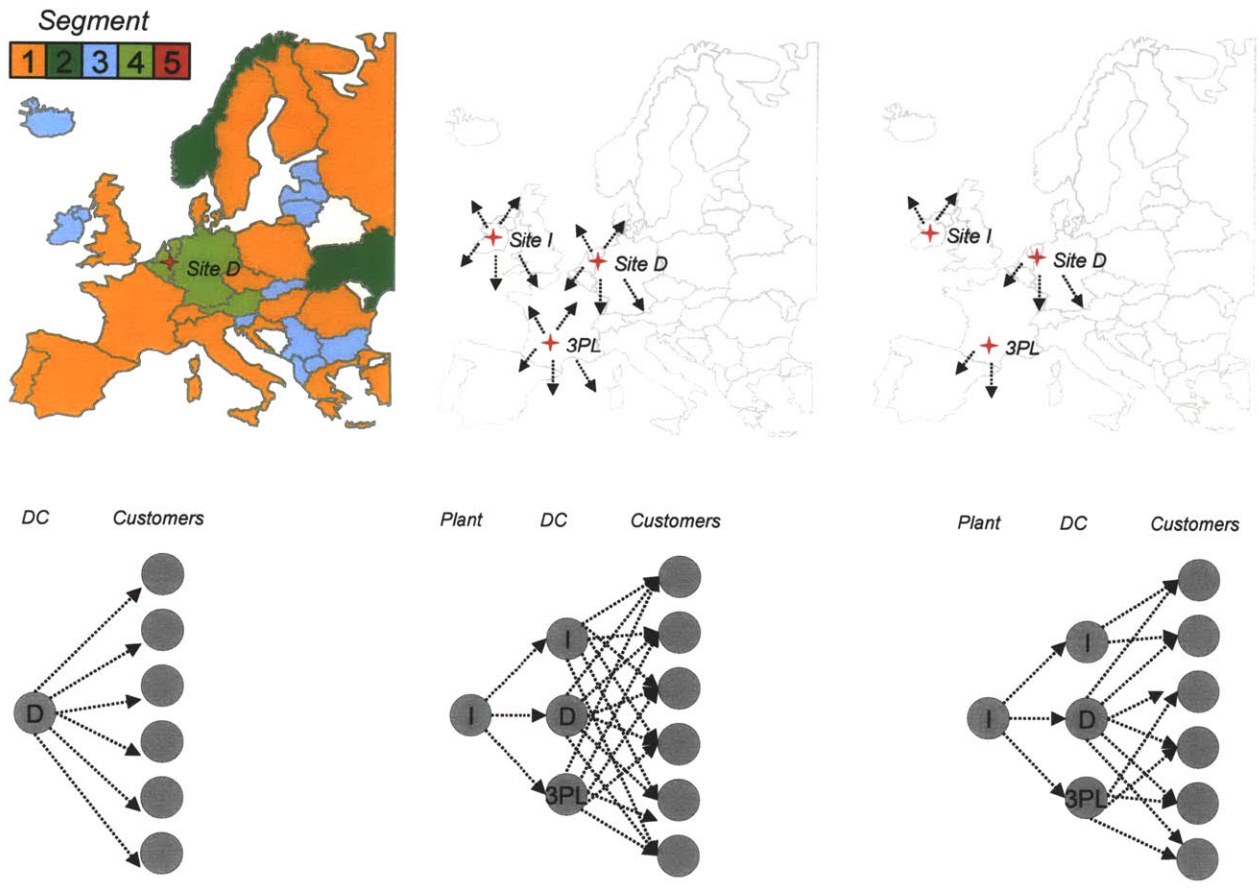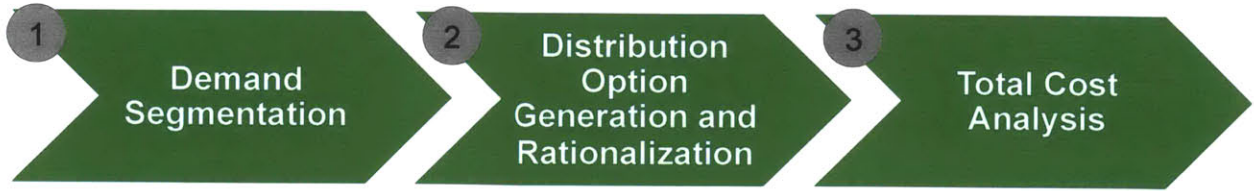
Figure 7 - Phased Distribution Network Solution Methodology

To contrast and compare our phased method to S&D's MILP method, we can approximately map their index sets and parameters to the phases or data that address those items using their notation. For some parameters, a direct map is not possible. For instance, the volume-weight of product l is addressed differently by our model – we assume that the product mix is constant for a given country and use the average shipment volume-weight instead.

Index sets:

$I \in \{countries\ served\}$ set of retailer locations

$J \in \{Site\ I, Site\ D, 3PL\ sites\}$ set of warehouse sites

$K \in \{Site\ I\}$ set of plant sites

L is a single commodity   set of product types

E determined by Phase 3 inventory analyses   set of possible capacity levels for warehouses

G is fixed for Site I   set of possible capacity levels for plants

Parameters:

fw_j^e from capital planning team in Phase 3   fixed annual cost of opening and operating a warehouse at site j, with capacity level of e

fp_k^g not applicable since Site I capacity is fixed   fixed annual cost of opening and operating a plant at site k, with capacity level of g

$d_i^l \in \{country\ level\ pack\ demands\ from\ Phase\ 1\}$ annual demand of retailer i for product l

wc_j^e determined by Phase 3 Inventory Analyses   capacity level e for warehouse j

$pc_k^g \in \{fixed\ Site\ I\ capacity\}$ capacity level g for plant k

$v^l \in \{average\ shipment\ volume\ to\ country\}$ unit volume (weight) of product l

cwr_{ij}^{lt} determined in Phase 2 cost filter and Phase 3 Inventory Analyses   unit cost of transporting product l by mode t from warehouse j to retailer k (including the warehouse operational costs for a unit of product l)

cpw_{jk}^{lt} determined in Phase 2 cost filter   unit cost of transporting product l by mode t from plant k to warehouse j (no need to include the manufacturing cost of product l at plant k since no plant decision must be made)

twr_{ij}^{lt} determined in Phase 2 lead time filter   delivery lead-time of product l from warehouse j to retailer i in mode t

$tpw_{jk}^{lt} \in \{truck\ time\ from\ Site\ I\ to\ warehouse\ j\}$ delivery lead-time of product l from plant k to warehouse j in mode t

$m^{lt} \in \{\infty\}$ since lead time must be met   monetary value per unit of lead-time for product l in mode t

wh_j^l is addressed by Phase 3 inventory analyses   annual inventory holding cost for one unit of product l at warehouse j

ph_k^l is addressed by Phase 3 inventory analyses   annual inventory holding cost for one unit of product l at plant k

$wsf_{ij}^{lt} \in \{\#\ shipments\ data\ from\ Phase\ 1\}$ service frequency of mode t for product l from warehouse j to retailer i

wsf_{ij}^{lt} is fixed at weekly shipments   service frequency of mode t for product l from plant k to warehouse j

We will see in the treatment of each of the phases that we address all facets of the S&D

formulation, but manage to simplify many of the tradeoffs optimized therein through observations and

assumptions about the system under analysis.

We first observe that there is a small set of sites. The network under analysis contains a single plant

site (Site I) for which the manufacturing capacity is fixed. On the other hand, there are several warehouse

sites (Sites D and I and 3PLs) for the warehousing capacity is variable, where expansion costs for Sites D

and I are accounted for in NPV analysis and 3PL capacity is considered variable without meaningful

expansion costs.

Historical analysis in Phase 1 enables us to set the service frequencies from warehouse to retailer

and from plant to warehouse to constants that we derive from historical analysis in Phase 1. This phase

also simplifies our analysis by characterizing demand on a country level rather than on an individual

customer level. In this phase, we also find we can simplify our analysis by serving all commercial SKUs

for a given country from a single site rather than serving some SKUs for a given customer in a country

from one site and some from another. Together, these two simplifications allow us to simulate an

optimization using binary decision variables optimizing whether a given country's total pack demand for

all products is delivered from warehouse j via transportation mode t rather than the more complicated

decision variable used by S&D that optimizes the fraction of customer i's demand for a given product l

delivered from warehouse j via transportation mode t.

Phase 2 adapts the lead-time facet of S&D's approach. Given non-negotiable lead-time

requirements, our method effectively sets the lead-time cost to an infinite number by filtering out any

lanes and transportation modalities that do not meet the lead-time requirements.

Phase 3 inventory analyses for various multi-country SKUs validate our assumption that we can

find a global optimum without taking into account a potential tradeoff between distribution and inventory

cost. We validate that assumption by showing that holding a given multi-country SKU in multiple

locations reduces the distribution cost and, thereby, the total network cost, significantly more than the resulting tradeoff in higher inventory holding cost. Finally, Phase 3 addresses the fixed-cost vs. variable-cost tradeoff inherent in S&D's method through the use of discrete NPV analysis.

Chapter 5: Demand Segmentation

The goal of this first phase is to characterize discrete markets served by the current distribution network in a way that allows new distribution network solutions to be compared in a defined and measurable manner. Furthermore, demand segmentation structures the data-gathering process for understanding the current state.

As discussed in Section 2.1, Company A uses a variety of distribution methods in different combinations depending on the unique demand characteristics and requirements of a given country. In some countries, the company uses the "classic distribution chain" of manufacturer-3PL-wholesaler-pharmacy-patient [26]. In other countries, Company A found that a different distribution chain is more optimal. With the knowledge that each distribution option has strengths and weaknesses, its existing in-country distribution network is optimized to the current circumstances. Since the problem scope excludes modifying the in-country distribution chain, a logical country-level delineation emerges.

On the country level, we find that various criteria relating to customer information, shipment characteristics, and distribution requirements such as those detailed in Figure 8 below can be used to segment the demand.

Category	Criteria
Customer information	• Type • Number • Pack Demand
Shipment characteristics	• Distance (demand geography) • Modality • Average shipment size • Quantity
Requirements	• Lead Time • Temperature control • Regulatory

Figure 8 - Distribution Network Segmentation Criteria

Although a variety of product SKUs exist, we make a simplifying assumption that the SKU mix will stay constant. Furthermore, we find that all commercial SKUs for a given country have sufficiently similar characteristics and requirements to allow us to make the simplifying assumption that it is always best to serve all SKUs for given country from a single site that can meet those requirements and distribution shipments with those characteristics to that geographic region at the lowest cost rather than serving some SKUs for a given country from one site and some from another. This enables us to use country total pack demand forecasts for a given implementation year to estimate future shipment quantities and, in Phases 2 and 3, costs.

For the purposes of Company A's distribution network, we can estimate future shipment quantities for two shipment categories: truck and parcel/air. Truck shipments have historically not been filled to capacity and are therefore schedule-driven, not volume-driven. Therefore, we may estimate the number of truck shipments by historical decisions made on the truck schedule under the (verified) assumption that pack volume shipped by truck will not increase enough to justify increasing truck frequency. Parcel shipments, on the other hand, are driven by volume. Therefore, we forecast the number of parcel shipments by multiplying per-country sales forecasts by historical numbers regarding number of packs per parcel for a given country:

$$country\_parcel\_shipments \ = \frac{country\_pack\_sales\_forecast}{country\_average\_packs\_per\_parcel}$$

In addition to shipment quantities, we find that customer lead-time requirements, average shipment size, and demand geography are very impactful in characterizing the pharmaceutical market demand segments. Figure 9 demonstrates how a given country's distribution chain might impact two of these criteria. If Company A uses a 3PL, distributor, or wholesaler to distribute the majority of its product in a given country, the majority of shipments to that country will replenish the 3PL's stock and therefore typically consist of both large and non-urgent scheduled shipments. On the other hand, if the majority of shipments ship directly from Company A's DC to patient-facing customers such as hospitals, pharmacies,

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or homecare providers, the DC must service these customer with urgent, next-day shipments, which generally consist of smaller shipments of a few packs.
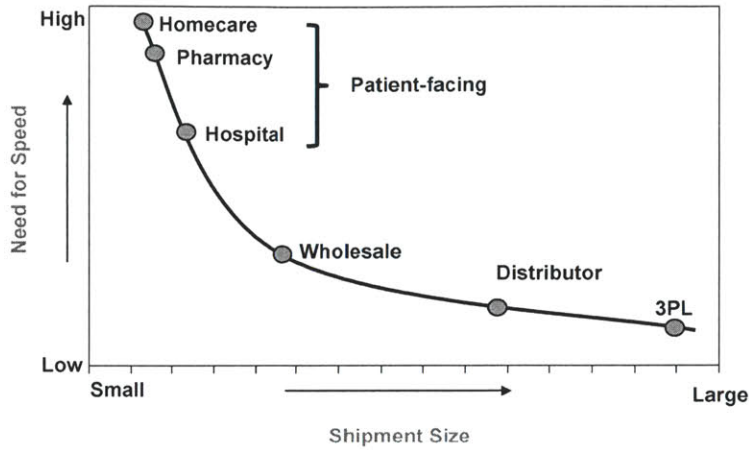
Figure 9 - Tradeoffs Between Speed and Shipment Size in Distribution Options

Demand geography plays a large role due to its impact on many other parameters. The geography determines its distance from the shipment origin (i.e. the distribution facility being decided upon), the possible shipment modalities such as road, sea, or airfreight, and the minimum possible lead-time with a given modality. This affects pharmaceutical goods in particular due to their temperature sensitivity. As described in Section 2.2, these products require use of either active cold chain ("ACC") methods of transportation or insulated shipping containers ("ISCs") passively cooled with cooling materials such as dry ice. Trucks and intermodal containers are two of the only transportation modes that are generally actively cooled, which leaves most parcel and airfreight passively cooled. These passively cooled ISCs are only qualified to adequately cool for certain lengths of time. In order to allow for longer distances and possible customs delays for more distant demand geographies, longer-rated ISCs can be used at the expense of larger, heavier, and more costly packaging that also costs more to ship.

The demand segmentation phase results in an easily referenced overview of the current distribution network that can be modeled in a spreadsheet such as the illustrative example below.

Country	Customer Type	Shipment Mode	Temperature Control	Pack Volume (K)	Trucks (#/yr)	Parcel/Air Shipments (K/yr)
A	Wholesaler	Air	ISC	20	0	0.1
B	Patient-facing	Parcel	ISC	15	0	5
C	Patient-facing	Parcel	ISC	2	0	0.4
D	LSP	Truck	ACC	300	52	0
E	Patient-facing	Parcel	ACC	50	0	10

Figure 10 - Example Output of Phase 1 Demand Segmentation (obfuscated)

From our discussion of Phase 1, we see that this phase is especially useful in identifying determining factors and establishing a framework around which future analyses can be structured. Furthermore, by creating an easily referenced spreadsheet such as exemplified in Figure 10, we may solicit opinions from multiple stakeholders throughout the company and initiate conversations about future decisions. These discussions can, in turn, inform the decision-making process started in Phase 2 and completed in Phase 3.

Chapter 6: Distribution Option Generation and Rationalization

The second phase first generates all possible distribution options that could potentially service the country demand segmented in Phase 1. In this case study, the options include shipment via various modalities from the existing Site D, the new site I, as well as any distribution locations available through 3PLs. For the purposes of this thesis, let us assume that Figure 11 is representative of the possible site options.

Figure 11 - Phase 2 Distribution Options (obfuscated)

Once we enumerate the possible distribution lane and modality options, we can then evaluate them on their ability to adequately service each of the customer segments generated in Phase 1 with a result similar to Figure 12 (note that the current distribution site, Site D, can acceptably service all current demand segments). As discussed in Phase 1, we assume that the optimal solution can be found by servicing all SKU demand for a given country from a single site. That assumption is also reflected in the example Phase 2 output table below.

Distribution Option	Acceptable Service to Country (via modality)			
	A	B	C	...
Site D	Y (road)	Y (parcel)	Y (parcel)	
Site I	Y (parcel)	N	Y (RoRo)	
3PL Site 1	Y (parcel)	N	N	
3PL Site 2	N	Y (road)	Y (parcel)	
3PL Site 3	N	N	N	

Figure 12 - Example Phase 2 Output

Here, adequate or acceptable service is determined by successfully passing through the lead-time, qualitative, and cost filters discussed in the rest of this chapter. The main goal of this phase is to reduce the complexity of the fine-grained comparative analysis in Phase 3 by using rougher filters. A further benefit to the manual filtering approach is that each of these characteristics (e.g. order arrival histograms or various qualitative factors) can be evaluated on a case-by-case basis rather than inputting a complete dataset ahead of time for an equivalent MILP. This filtering approach is illustrated below.
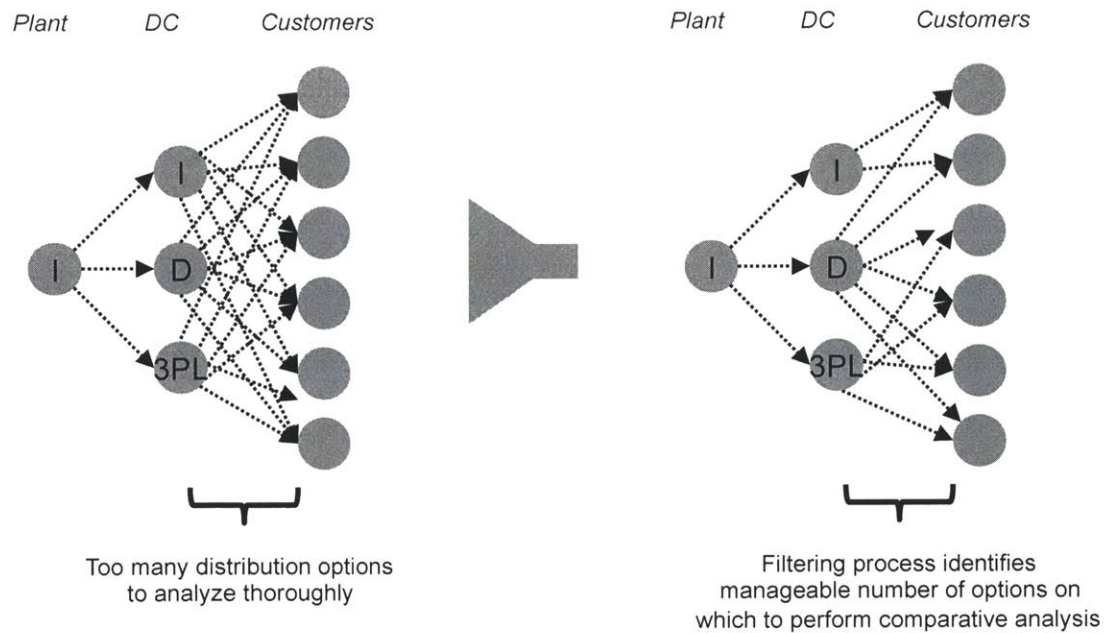

Too many distribution options to analyze thoroughly

Filtering process identifies manageable number of options on which to perform comparative analysis

Figure 13 - Filtering process illustration

6.1 Lead Time Filter

The most important deciding factor on whether a given option can acceptably service a demand segment is its ability to satisfy customer lead-time requirements under typical circumstances. We explore all potential shipment modalities for a given option. For instance, let us assume that Site I (i.e. Ireland) could service England using road freight plus LoLo, road freight plus RoRo, and airfreight modalities. Furthermore, England's in-country distribution consists of direct shipment to pharmacies and hospitals, which implies a one-day lead-time requirement. We might then determine that road freight plus LoLo would take two days to reach the British customers while road freight plus RoRo and airfreight both meet the one-day lead-time requirement. In this case, we have eliminated the option of servicing England by using road freight plus LoLo from Site I, but have not eliminated Site I as an option entirely. A given site option is only eliminated if all modalities fail to meet the Phase 2 requirements for a given demand segment. This filter might be considered an optimization where the cost of lead-time above and beyond the customer requirement is infinite.

A slight twist to this issue becomes apparent when examining lead-time with express parcel service, which is the typical mode of transport for next-day shipments to patient-facing entities such as pharmacies and hospitals. If we define lead-time as the time between receipt of the customer's order and arrival of the package at the customer's doorstep, we note that several steps must occur between these two events (See Figure 14). After the customer's order is received, the warehouse must "fill" the order (i.e. pick off the shelves and pack into insulated shipping containers). This must be done before the last pickup by the parcel carrier service (e.g. UPS, FedEx, etc.). In order to make sure that there is sufficient time to fill the order, we set an order cutoff time by which a customer can be guaranteed to receive their shipment next-day. The timing of the last pickup of the day will depend on the parcel carrier's flight schedules to their hub airport, which are in turn determined by the location from which the package is picked up. Therefore, the pickup time at Site D might be different than the pickup time at Site I or at one of the 3PL sites.
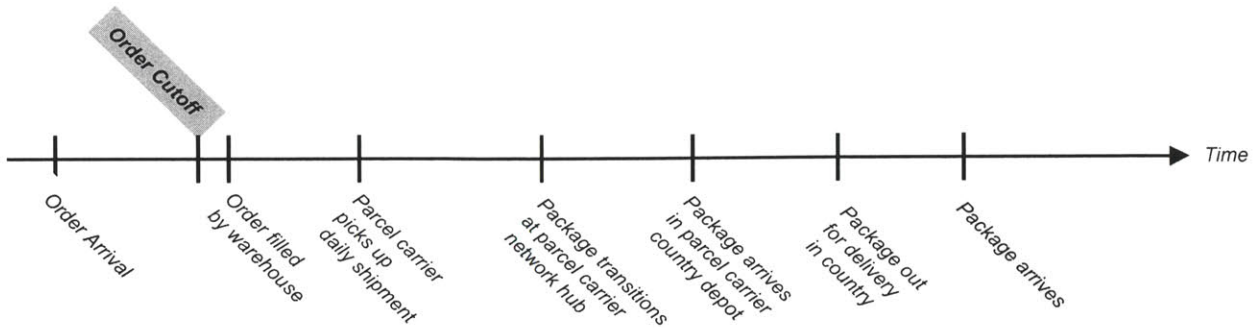
Figure 14 - Express parcel service order timeline

If we change the distribution site that serves a given country from Site D to some other site option and if the resulting order cutoff time is earlier than the status quo, customers in that country would effectively be required to submit orders earlier than they are currently used to with service from Site D. We can evaluate the effect of this change on sales by creating a histogram of the current order placement time, such as illustrated in Figure 15.
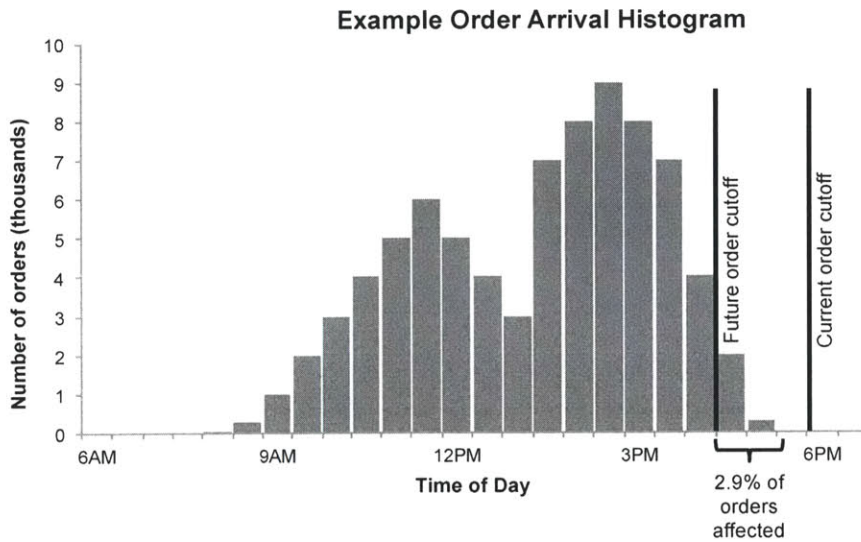
Figure 15 - Example Order Arrival Histogram

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By comparing the resulting histogram against the new order cutoff time, we can determine what percentage of customer orders would be affected. In the above histogram example, we expect that 2.9% of future orders would be affected. This information can then be discussed with the sales team to determine whether that level of impact would be acceptable. If that level of impact is not acceptable, we could further investigate potential mitigation methods or we could remove the option.

6.2 Qualitative Filter

After analyzing lead-time related factors, we can evaluate the remaining site-modality options on a variety of qualitative criteria, such as those listed below. Note that we also consider and reduce risk at this point.

- *Ability to meet implementation timelines*: If a given option would take longer than the required transition date to implement, we may eliminate it. For example, if it would take too long to expand Site I's present warehouse capacity to meet the additional demand to service England, that might remove Site I as an option.

- *Reliability of service (supply disruption risk)*: This point evaluates the risk of supply disruption and distribution delays to time-sensitive customers, as well as the availability of alternative methods of meeting lead times under adverse circumstances. For instance, Site I might experience weather-related delays of several days due to stormy seas if it uses RoRo as its primary mode of transport. This could exclude using RoRo from Site I as an option to serve that demand segment. However, if the risk of weather-related delays can be mitigated by backup shipments via airfreight, it remains an acceptable option. Similarly, if Site I typically ships goods to a given country via airfreight and there is a risk of a volcano eruption that disrupts air travel, this risk

might be mitigated by RoRo shipment to an unaffected airport. Note that this latter example may nevertheless be unacceptable if the RoRo shipment still fails to meet the necessary lead times.

- *Slack distribution capacity*: There should be sufficient capacity for a given modality from a given site to serve all demand segments expected for that site-modality combination. Furthermore, since we expect demand will continue to grow and since demand forecasts will inevitably be inaccurate, additional slack capacity is desirable. If we find, for example, that we can send weekly replenishment shipments to a 3PL in France from Site I via LoLo, but that future demand might require semiweekly shipments that are not possible with existing commercial shipping schedules, there is a risk that insufficient slack distribution capacity via this modality could compromise future operations. Therefore, this example would require removing that site-modality option from the list of options that could serve France. Uncertainty in future demand requires sufficient slack capacity to handle possible increased capacity requirements.

In order to gain buy-in from company stakeholders, the ability to apply such qualitative filters is imperative.

6.3   Cost Filter and Minimization

With the list of possible options further reduced, we can perform a rough cost evaluation to determine what site-modality combinations make sense to serve a given country. Using estimates on the number of shipments for different lanes from Phase 1, we can approximate future distribution and packaging costs to service a given demand segment with a given site-modality. To illustrate this point, as well as the need for this step, let us consider a distribution option shipping large-volume shipments from Ireland to a wholesaler in Portugal via airfreight. While we are able to meet the lead time requirements for the wholesaler and we expect that we are able to meet implementation deadlines, mitigate risk of supply disruption via RoRo shipment, and there is sufficient slack capacity to handle possible increased capacity

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requirements, we calculate the approximate shipment and packaging costs of such a solution and find them unreasonably high compared to a RoRo solution from Ireland as well as current truck distribution from Site D, which both have lower shipment costs and lower packaging costs since those options would be actively cooled and can use simpler, cheaper cardboard packaging. By filtering out many such nonsensical solutions, we can reduce the set of possible distribution options down to a manageable number for in-depth evaluation in Phase 3. This filter is in essence a first pass at minimization.

Distribution costs for Company A are split between either truck or parcel/air shipments to match the categories for number of shipments from Phase 1. Since Company A only uses full truck load (versus shared partial truck load) load shipments for improved security and quality-control, the cost of truck shipments may be calculated by multiplying the price of a truck traveling a given lane by the number of trucks traveling that lane each year:

$$total\_truck\_shipment\_cost = \sum_{\forall \, lanes} price\_truck\_lane \cdot number\_shipments\_lane$$

For shipments originating from new sites, we can solicit quotes from trucking companies for the new lanes to determine the cost to service that new lane.

On the other hand, parcel and airfreight distribution costs will both depend on the size and weight of the shipment as well as on the specific shipping lane. Therefore, we estimate parcel distribution costs by multiplying the forecasted number of shipments by the average historical cost per parcel:

$$total\_parcel\_shipment\_cost = \sum_{\forall \, lanes} average\_historical\_parcel\_price \cdot number\_shipments$$

Similarly, when adapting this calculation for new shipment lanes, we must modify the average historical parcel price. We assume that the parcel size and weight will stay constant and can get comparative quotes for the new lanes to determine the price difference between the new and old lanes. This then allows calculation of total parcel shipment cost including for new lanes.

In using these distribution cost forecasting techniques, we make several interesting observations. Mainland European countries in which Company A directly serves thousands of hospitals and pharmacies would be significantly more costly to distribute to from Site I. On the other hand, truck shipments to bulk customers such as distributors and wholesalers as well as to 3PLs cost approximately the same amount to ship from Site I to a mainland DC (e.g. Site D or a 3PL site) and then to the customer as the cost to ship directly from Site I to the customer. Finally, it costs approximately the same to serve international customers outside of mainland Europe via airfreight from Site I as it would from a mainland DC.

The choice of both distribution site and modality can also affect the cost of shipping containers. If it is possible to change a previous passively cooled transportation mode such as parcel delivery to an active cold chain transportation mode such as truck delivery, for instance, the cost of expensive insulated shipping containers can be avoided. Alternatively, if changing to a new site that is significantly further away from the demand point than Site D while maintaining a parcel shipment mode, the size of the ISC might need to be increased in order to allow for the longer shipping time in ambient temperature conditions, thereby increasing the cost of the packaging. We can determine a given lane's packaging cost by using historical statistics on shipper types used and their respective costs and sizes. From this information, we can calculate the average shipper cost for a given lane and multiply that cost by the number of shipments using that lane:

$$total\_packaging\_cost = \sum_{\forall\ lanes} packaging\_cost \cdot number\_shipments$$

Information about the alternative containers (e.g. non-insulated cardboard packaging or larger ISCs) for a given distribution option allows us to determine alternative packaging cost as a multiplier for that lane.

Using both distribution and packaging cost estimates, we can quickly identify further site-modality options that do not make sense. The remaining options can then be transitioned to Phase 3 for a thorough business case analysis.

Chapter 7: Total Cost Analysis

In the third phase, we use the top options drawn from Phase 2 to generate complete networks that can be thoroughly analyzed and compared to find the optimal, lowest total-cost solution. As seen in the below example, one of the top site-modality distribution options is chosen for each demand segment to create a complete network solution.

| Distribution Option | Acceptable Service to Country (via modality) | | | |
	A	B	C	...
Site D	Y (road)	Y (parcel)	Y (parcel)	
Site I	Y (parcel)	N	Y (RoRo)	
3PL Site 1	Y (parcel)	N	N	
3PL Site 2	N	Y (road)	Y (parcel)	
3PL Site 3	N	N	N	

Figure 16 - An example distribution network solution

The number of complete distribution network solutions generated will largely depend on the number of options that have been transitioned from Phase 2. In order to make Phase 3 manageable, Phase 2 should sufficiently reduce the number of options to choose from. This project reduced hundreds of possible network combinations down to three top candidates to evaluate in Phase 3.

We can then characterize each complete network solution by the financial attributes detailed in Figure 17 below.

Figure 17 - Financial Criteria

Category	Criteria
Startup Costs	• Capital expenditure to build out warehouse space
Ongoing Costs	• Labor (e.g. handling, receiving, etc.)
	• Utilities & Maintenance
	• Distribution costs
	• Packaging costs

While some of the financial criteria, such as distribution and packaging costs, could already be characterized in Phase 2, the other costs depend on network-wide distribution and inventory decisions. Each distribution network combination created in Phase 3 allocates a different level of distribution volume to a given site. This volume, in large part, can be used to estimate labor-related costs by appropriately scaling current site labor costs by the difference between current and future distribution volumes. Inventory decisions, on the other hand, determine necessary warehouse capacity and resulting capital expenditure and utility and maintenance costs.

7.1   Labor Cost Estimation by Distribution Volume Analysis

For a given distribution network solution, each site will take responsibility for supplying a portion of the total demand. The implication of this is that Site D will distribute less than its original volume in many proposed solutions and Site I will at the very least need to ship replenishment volume to Site D. In the below simplified example (Figure 18), Site D used to directly ship to Customer A and B. However, in the possible distribution network solution to its right, Site D then only services Customer A's demand (d_a). Site I takes over Customer B's demand volume (d_b) and replenishes Site D in large shipments on a less-frequent schedule for the sum of the demand it services – in this case only d_a (r_a). Therefore in the "before" case, the total distribution volume satisfied by Site D equals $d_a + d_b$. In the "after" case, Site D has fewer shipments (only d_a), but Site I not only has to now ship to Customer B (d_b), but also replenish Site D (r_a).

Noting that amount of time it takes to pick, pack, and ship individual customer shipments (e.g. d_a or d_b) is significantly higher than the amount of time it takes to load an equivalent number of product via pallets onto a truck for a replenishment shipment (e.g. r_a), we can estimate the total network workload for the "after" case will be slightly higher than in the "before" case. Then, in order to calculate the total labor

cost, we can multiply the site-specific labor rate on top of the number of man-hours at a given site, which we calculate from the site's distribution workload.
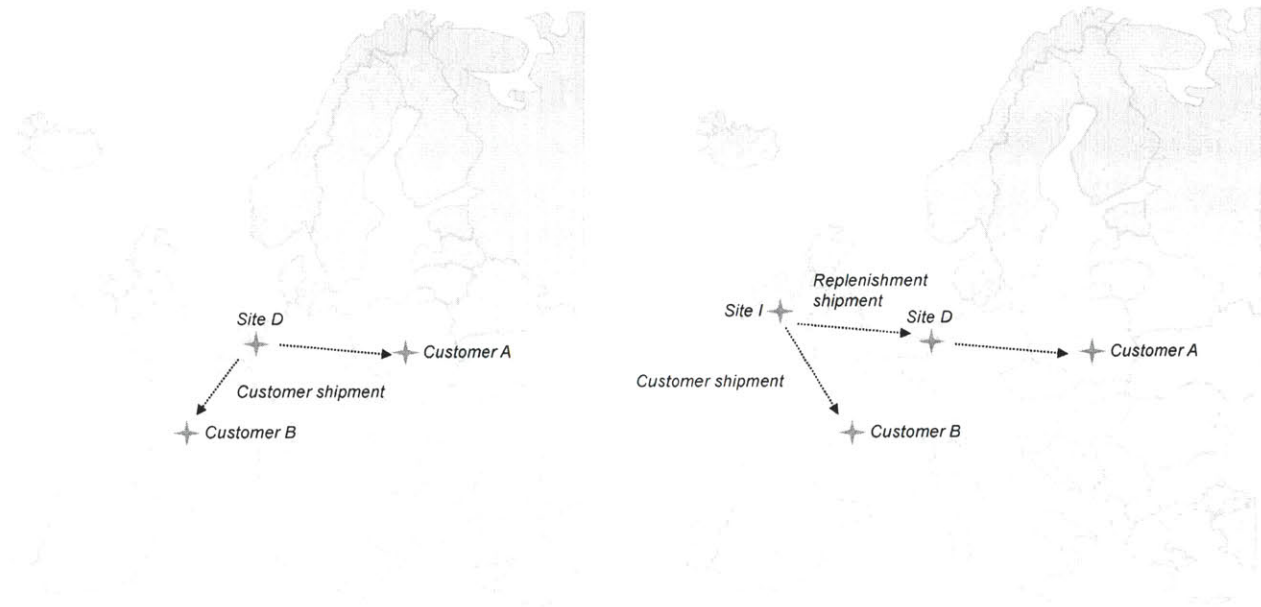
Figure 18 - Example Distribution Volume "Before" and "After" Scenarios

7.2 Inventory Analyses

We evaluate the impact of various distribution network solutions on inventory for two reasons. Firstly, we must determine each solution's required distribution center warehouse size. Secondly, we must ensure the validity of our assumption that we can find a global optimum without taking into account a potential tradeoff between distribution and inventory cost. We can validate this by showing that the decrease in transportation cost caused by holding a given SKU in multiple locations outweighs the additional holding cost. Fortunately, given that most multi-country SKUs in Company A are clustered in similar geographic regions and Phase 2 has demonstrated that most of the region clusters are best served by the same distribution site, only a minimal number of SKUs that have lower distribution costs when served by multiple sites must be evaluated.

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Company A's corporate inventory policies for a given SKU determines expected inventory for that SKU at a given site. Three different types of inventory are utilized: 1) strategic safety stock, 2) operational safety stock, and 3) cycle stock. These are depicted in Figure 19 below.

Upper Planning Limit =
Lower Planning Limit +
replenishment cycle stock

Planned Average =
Lower Planning Limit + 50% of cycle stock

Lower Planning Limit =
Operational + Strategic Safety Stock

Operational Safety Stock

Strategic Safety Stock
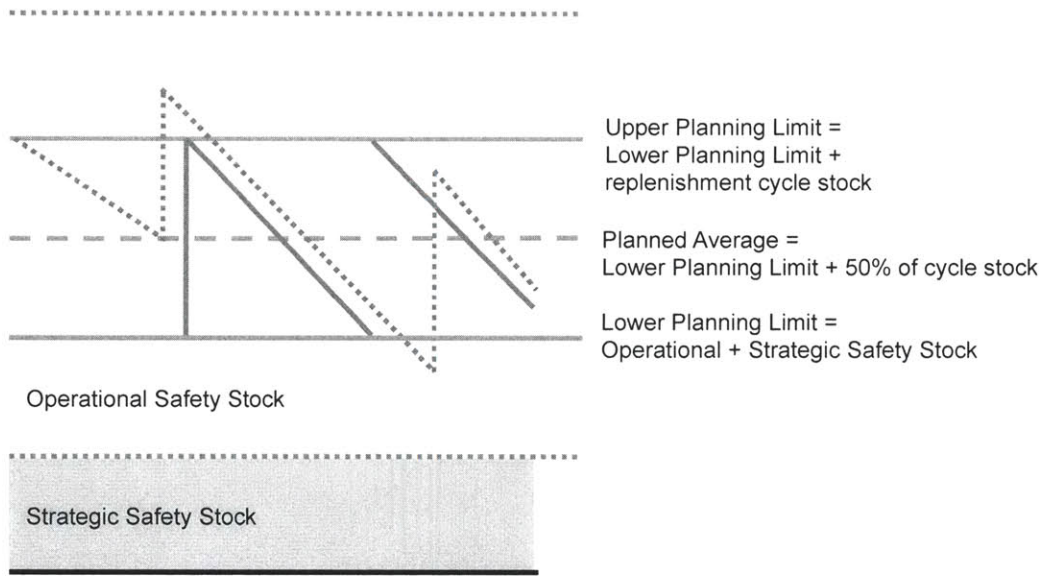
Figure 19 - Inventory Definition Diagram

Strategic safety stock is inventory set aside to solely mitigate risk of supply disruption in extreme and unlikely situations. Therefore, quantities of strategic safety stock are decided on a network (rather than site) and SKU level based on risk assessment of supply chain disruptions (e.g. earthquakes, storms, power outages, strikes, etc.). These assessments result in target quantities set to so-called months of forward coverage (MFC) – the quantity of inventory necessary to satisfy one month of demand for that product. FDP strategic safety stock, such as that which is the focus of this discussion, is then allocated based on the proportion of total SKU demand served by a given site.

Operational safety stock, on the other hand, is calculated on a site-by-site and SKU-by-SKU basis using the traditional safety stock formula:

$$z \cdot \sqrt{\mu_{LT} \cdot \sigma_D{}^2 + \mu_D{}^2 \cdot \sigma_{LT}{}^2}$$

Here, z equals the inverse of the standard normal cumulative distribution for the desired service level[3], which is generally chosen to be above 99% given the critical importance of satisfying medical demand, and LT is the total lead-time. Total lead-time in the case is defined by the sum of the IDP inspection process lead-time, the manufacturing lead-time to package the IDP and product FDP and the shipping and receiving lead-time. This shipping and receiving lead-time, in turn is defined as the sum of the time between replenishments from the new manufacturing Site I to the distributing site and the shipping lead-time, which is typical of a fixed time-period inventory model or periodic review (T, M) inventory model.

As discussed extensively by Eppen and Martin (1988) [27], in order to obtain correct results using this safety stock formula, we must make and verify two key assumptions: 1) the lead-time distributions are unimodal and 2) demand increments are independent of time and, therefore, that σ_D increases proportionally to the square root of lead-time. In this case study, the lead-times are indeed unimodal due to the fact that the lead-time distribution is primarily affected by the inspection lead-time – both manufacturing lead-time and shipping and receiving lead-time contribute minimally to the total lead-time variability. We also determine that σ_D increases proportionally to the square root of lead-time. Rosenfield (1994) [27] suggests that we may relate forecast errors (σ_D) to demand (μ_D) by a generalized power formula:

$$\sigma_D = K \cdot LT^{\alpha} \cdot \mu_D{}^{\beta}$$

As a result, we may determine independence between demand increments and time by establishing that $\alpha = \beta \cong 0.5$. Values higher than 0.5 would indicate spatial or serial correlation. By using historical data on demand forecasts for various time increments, we confirm that the α and β parameters indicate demand increments independence with respect to time.

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[3] The equivalent function in Microsoft Excel would be NORMSINV(service level)

Cycle stock is similarly site- and SKU-specific, where each site's cycle stock is similarly replenished by Site I. Here, the average demand (μ_D), time between replenishments (τ_R), and shipping lead time (τ_S) determine the inventory levels:

$$\mu_D \cdot (\tau_R + \tau_S)$$

Since each network solution calls for a given site to serve different combinations of customer segments and the amount held at each site is roughly set by its proportion of demand, we see that inventory at a given site will differ dramatically based on the network solution being analyzed.

With the site inventory defined for all sites in a given network solution, we can first calculate total necessary warehouse size for each site. This information can be used by the capital planning team to approximate the resulting required capital expenditure as well as the resulting utilities and maintenance costs.

We can also use these formulas determine the impact of holding a given SKU in multiple locations for the number of multi-country SKUs. While some SKUs that Company A sells are designed for sale in a single country, others are designed for multiple languages and with other features that allow for sale in multiple countries. Since Phase 2 determined various possible shipment lanes and storage locations based on country-level demands and requirements, we must evaluate the impact of splitting apart a centralized inventory of such a multi-country SKU. We have so far hypothesized that the increased network inventory costs are minimal relative to the distribution cost benefits of holding such a SKU in multiple locations. Using the above inventory analysis methods for only those SKUs that we determined in Phase 2 might benefit from being served from multiple sites, we find that the effect of demand disaggregation on a given product SKU indeed has a minimal impact on the overall network safety stock. For a given SKU, the total required safety stock in the network (SS_T) is given by the sum of safety stock at each site (SS_i). The analysis shows that $SS_T \cong \sum_{i \in I} SS_i$ and, moreover, that the minute increase in holding costs caused by holding a given SKUs inventory in multiple locations is outweighed

by a significantly larger decrease in transportation costs. With this knowledge, we find that we can safely assume that our country-level, constant-SKU-mix treatment of this problem will still give us an optimal solution.

7.3   3PL Cost Assessment

While internal costs may be easily calculated by experts with knowledge of labor rates, construction costs, utility rates per square meter, etc., outsourced costs can vary wildly depending on the level of market competition as well as any given 3PL's expertise and quality. 3PL engagement typically occurs through the use of "request for proposal" ("RFP") documents, which are circulated among several 3PL candidates. These documents generally outline the services that the customer (i.e. Company A) expects the 3PL to perform and provide the necessary data to allow the 3PL to accurately estimate their internal costs (e.g. expected distribution volumes, inventory policies, temperature requirements, etc.). The 3PLs then respond to this RFP with price quotes and information about their capabilities that enable the customer to ultimately choose their preferred vendor.

For a more expeditious process, such as that required for this project, we can alleviate concerns about 3PL quality and performance by preselecting 3PL candidates that Company A has worked with in the past and about which Company A knows their performance in distributing would suffice. We then send RFPs to these preselected 3PL candidates with price quote requests about the various distribution network solutions for which 3PL sites are required. In general, we find that a 3PL solution has negligible startup costs but substantive variable costs that must be taken into account in the NPV analysis.

7.4 NPV Analysis

With the assumption that no impact to revenue will occur as a result of the distribution network modifications, a net present value ("NPV") comparison purely based on costs may be used. An NPV analysis enables us to determine the comparative impact of further upfront investment to, for example, build out distribution and warehousing capacity versus the higher ongoing variable costs of outsourcing warehousing and distribution to a 3PL. Furthermore, an NPV analysis of the startup and ongoing costs provides a single number that may be readily compared between potential network solutions, where:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t}$$

Startup costs are included as negative numbers in CF_0, while ongoing costs are included as subsequent negative CF_t values. The discount rate r uses the corporate discount rate for Company A, while the time horizon n is similarly set by standard company practice. Net present value, in this case, is always negative and the least-negative solution is most preferable.

Chapter 8: Summary

8.1 Conclusions

The project resulted in several key conclusions. First, when distributing directly to customers, the ability to meet lead-time requirements is critical in narrowing down the possible distribution options. Second, the negative impact of splitting apart multi-country SKU inventory among multiple distribution locations is significantly smaller than its positive impact on distribution costs. This enables a much simpler analysis. Finally, the ability to discuss the method of analysis and its conclusions in phases is invaluable in ensuring efficient integration into company-wide decision-making.

The project results will be used in informing future distribution network decisions by Company A's executive leadership team. These decisions will depend not only on these distribution-focused results, but also on other considerations regarding Company A's supply chain that will be evaluated in separate work streams. Given the sensitivity around the possibility of these decisions impacting both sites and their employees and given that the decisions have yet to be finalized, no further detailed and specific conclusions may be presented in this thesis.

8.2 Methodology Discussion

The problem under discussion in this thesis uses a phased problem-solving approach. We choose this approach to enable flexibility, thorough analysis, and collaboration. Since pharmaceutical industry quality and regulatory steps occupy long periods of time after building out capacity, the analysis to determine the optimal distribution network and, thereby the optimal use of Site I becomes extremely time sensitive. As Camm and Chorman (1997) [18] find in their work with Proctor & Gamble, we find that our phased approach both improves intra-company collaboration and speeds up the decision-making process. The phased collaborative approach also helps address some of the cultural and political difficulties of making

changes to a distribution network that many employees at Company A already consider adequate. In conjunction with the phased approach, the use of familiar spreadsheet models such as those recommended by Smith (2003) [20] further enhances collaboration. These models enable knowledgeable team members to quickly identify and correct errors in assumptions and analysis.

While a processor-heavy MILP solving approach such as that used by Sadjady and Davoudpour (2011) [17] and others is not used, the approach we use is no less rigorous. Instead, we find that the problem-solving methodology is commensurate to the problem at hand – good modeling requires that we not use a method more powerful than we need. We similarly analyze and optimize fixed and variable costs of opening and operating facilities and both shipping and holding product. Lead times and service frequency are, however, fixed at values that we determine through collaboration with company experts in distribution, warehousing, and commercial relationships. Perhaps the largest determining factor in choosing our more manual, qualitative, and collaborative approach is the need to discretely evaluate transportation modes on lead-time related and qualitative factors. Without thoroughly filtering each site-modality against these factors, Company A would risk inadequately serving its patients. Unlike Constantine (2009) [21] and Feller (2008) [22], we choose to consider risk as an eliminating factor rather than as a comparative factor in this thesis.

8.3   Future Research Possibilities

Time pressure factors highly in the problem-solving approach used in this thesis. Decisions regarding the use and capability enhancement of Site I required expeditious analyses that excluded the possibility of using more sophisticated problem-solving techniques. Several extensions to the existing analyses would be of interest in future evaluations: 1) multi-period analysis, 2) stochastic demand analysis, and 3) use of AHP decision-making techniques. A multi-period analysis would improve the existing single-period analysis given the likelihood of future site expansions given future increased

demand. On the same note, given that future demand becomes more uncertain as we forecast further and further into the future, a stochastic analysis of demand's effect on the optimal solution would be beneficial. Finally, although the collaboration afforded by the problem-solving methodology used in this thesis significantly improved the quality of analysis, further rigor could have been introduced into the manner of collaboration by the use of AHP decision-making techniques.

Appendix 1: Sadjady and Davoudpour's Problem Formulation

Index sets:

I	set of retailer locations, indexed by $i \in I$
J	set of potential warehouse sites, indexed by $j \in J$
K	set of potential plant sites, indexed by $k \in K$
L	set of different product types, indexed by $l \in L$
T	set of available transportation modes, indexed by $t \in T$
E	set of possible capacity levels for warehouses, indexed by $e \in E$
G	set of possible capacity levels for plants, indexed by $g \in G$

Parameters

fw_j^e	fixed annual cost of opening and operating a warehouse at site j, with capacity level of e
fp_k^g	fixed annual cost of opening and operating a plant at site k, with capacity level of g
d_i^l	annual demand of retailer i for product l
wc_j^e	capacity level e for warehouse j
pc_k^g	capacity level g for plant k
v^l	unit volume (weight) of product l
cwr_{ij}^{lt}	unit cost of transporting product l by mode t from warehouse j to retailer i (including the warehouse operational costs for a unit of product l)
cpw_{jk}^{lt}	unit cost of transporting product l by mode t from plant k to warehouse j (including the unit manufacturing cost of product l at plant k)
twr_{ij}^{lt}	delivery lead-time of product l from warehouse j to retailer i via mode t
tpw_{jk}^{lt}	delivery lead-time of product l from plant k to warehouse j via mode t
m^{lt}	monetary value per unit of lead-time for product l in mode t
wh_j^l	annual inventory holding cost for one unit of product l at warehouse j
ph_k^l	annual inventory holding cost for one unit of product l at plant k
wsf_{ij}^{lt}	service frequency of mode t for product l from warehouse j to retailer i
psf_{jk}^{lt}	service frequency of mode t for product l from plant k to warehouse j

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Decision variables

X_{ij}^{lt} fraction (with respect to d_i^l) of retailer i's demand for product l delivered from warehouse j via transportation mode t

Y_{jk}^{lte} fraction (with respect to wc_j^e) of product l delivered from plant k to warehouse j with capacity level of e via transportation mode t

W_j^e binary variable equals to 1 if a warehouse with capacity level e is opened at site j, otherwise to 0

P_k^g binary variable equals to 1 if a plant with capacity level g is opened at site k, otherwise to 0

Considering the above notation, the model can be stated as follows:

Problem P.

$$
MinZ_P = \sum_{j \in J}\sum_{e \in E} fw_j^e W_j^e + \sum_{k \in K}\sum_{g \in G} fp_k^g P_k^g + \sum_{i \in I}\sum_{j \in J}\sum_{l \in L}\sum_{t \in T} cwr_{ij}^{lt} d_i^l X_{ij}^{lt}
$$
$$
+ \sum_{j \in J}\sum_{k \in K}\sum_{l \in L}\sum_{t \in T}\sum_{e \in E} cpw_{jk}^{lt} wc_j^e Y_{jk}^{lte} + \sum_{i \in I}\sum_{j \in J}\sum_{l \in L}\sum_{t \in T} m^{lt} twr_{ij}^{lt} d_i^l X_{ij}^{lt}
$$
$$
+ \sum_{j \in J}\sum_{k \in K}\sum_{l \in L}\sum_{t \in T}\sum_{e \in E} m^{lt} tpw_{jk}^{lt} wc_j^e Y_{jk}^{lte} + \sum_{i \in I}\sum_{j \in J}\sum_{l \in L}\sum_{t \in T} \frac{1}{2} wh_j^l ws f_{ij}^{lt} d_i^l X_{ij}^{lt}
$$
$$
+ \sum_{j \in J}\sum_{k \in K}\sum_{l \in L}\sum_{t \in T}\sum_{e \in E} \frac{1}{2} ph_k^l ps f_{jk}^{lt} wc_j^e Y_{jk}^{lte}
$$

S.t.

$$
\sum_{j \in J}\sum_{t \in T} X_{ij}^{lt} = 1 \quad \forall\, i \in I, l \in L \tag{1}
$$

$$
\sum_{i \in I}\sum_{l \in L}\sum_{t \in T} d_i^l v^l X_{ij}^{lt} \le \sum_{e \in E} wc_j^e W_j^e \quad \forall j \in J \tag{2}
$$

$$
\sum_{e \in E} W_j^e \le 1 \quad \forall j \in J \tag{3}
$$

$$
\sum_{i \in I}\sum_{t \in T} d_i^l v^l X_{ij}^{lt} \le \sum_{k \in K}\sum_{t \in T}\sum_{e \in E} wc_j^e Y_{jk}^{lte} \quad \forall j \in J, l \in L \tag{4}
$$

$$
\sum_{j \in J}\sum_{l \in L}\sum_{t \in T}\sum_{e \in E} wc_j^e Y_{jk}^{lte} \le \sum_{g \in G} pc_k^g P_k^g \quad \forall k \in K \tag{5}
$$

$$
\sum_{g \in G} P_k^g \le 1 \quad \forall k \in K \tag{6}
$$

$$
X_{ij}^{lt} \ge 0 \quad \forall i \in I, j \in J, l \in L, t \in T \tag{7}
$$

$$
Y_{jk}^{lte} \ge 0 \quad \forall j \in J, k \in K, l \in L, t \in T, e \in E \tag{8}
$$

$$
W_j^e \in \{0,1\} \quad \forall j \in J, e \in E \tag{9}
$$

$$
P_k^g \in \{0,1\} \quad \forall k \in K, g \in G \tag{10}
$$

Glossary

ACC: Active Cold Chain

AHP: Analytic Hierarchy Process

COGS: Cost of Goods Sold

DP: Drug Product

DS: Drug Substance

FDP: Finished Drug Product

FLP: Facility Location Problem

FMEA: Failure Mode Effects Analysis

IDP: Inspected Drug Product

ISC: Insulated Shipping Container

LGO: Leaders for Global Operations

LoLo: "Lift-on lift-off" modality

MFC: Months of forward coverage

MILP: Mixed-integer linear problem

NPV: Net present value

RFP: Request for proposal

S&D: Sadjady and Davoudpour

3PL: Third-party logistics provider

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