Developing a Strategic Roadmap for Supply Chain Process Improvement in a Regulated Utility

by

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B.S. Industrial Engineering,
Georgia Institute of Technology, 2004

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
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Developing a Strategic Supply Chain Process Improvement Roadmap for a Regulated Utility Supply Chain

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Brent E. Yoder

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Abstract

This thesis covers work done at Tracks Energy, a regulated utility, to develop a strategic roadmap for supply chain process improvement. The focus of Tracks Energy has always been on keeping the lights on and the gas flowing for its customers, and the organizational structure of the company has been aligned by functional expertise to accomplish this goal. Existing supply chain operations span across the areas of responsibility for four senior executives and ten different operational groups. The cost and responsiveness of the supply chain has been negatively impacted by groups working to improve performance directly associated with their tasks, at the expense of the supply chain as a complete system.

We propose a methodology for developing a strategic supply chain process improvement roadmap based on process map development, benchmarking, and data analysis to outline projected performance. We also present two different inventory models for developing inventory policies based on minimizing total material cost. The first inventory policy model applies a common framework based on stochastic optimization using normal distribution assumptions for demand and lead time. The objective of this model is to minimize costs over an infinite horizon given desired service levels. The second model is a multi-period model adapted from a robust framework. The objective of the second model is to minimize costs given unfavorable demand bounded by potential values unrestricted by a specific probability distribution function.

The strategic roadmap for supply chain process improvements presented in this thesis is currently being pursued through the development of a newly developed supply chain management team. The opportunities presented as a strategic roadmap represent the potential for significant capital and operational savings by focusing on the end to end supply chain over individual department functions.

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Special thanks also go to my MIT Sloan advisor, Georgia Perakis, and her student Gonzalo Romero, for providing generous technical guidance, and expert insight to shape the body of work covered in this thesis. I am grateful for the effort of my Engineering Systems Division advisor, Mort Webster, whose support and perspective of the regulated utility industry was invaluable for me to successfully complete this project.

I also wish to express my sincere appreciation to my parents and my brother for continuously supporting my development in both my personal and professional life through all of my endeavors.

Finally, and most importantly, I would like to thank my wife Mailee for her unwavering support and encouragement throughout this two year adventure of our lives together.

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Disguised Information

This thesis was prepared in part based on the author's 6 month internship experience working with a large regulated electric and natural gas utility in the United States. To protect sensitive information and to ensure that proprietary information is not disclosed, the company's name is disguised as Tracks Energy. Additionally, information will be protected by disguising sensitive data, masking identifiable sources, and removing the scale on a number of graphs.

Chapter 1: Introduction

1.1 Company Overview

Tracks Energy is a large investor owned energy company in the United States, and is primarily focused on the transmission and distribution of electricity and natural gas. The company's transmission and distribution service areas span three different state regulatory regions. Tracks Energy was founded in the late 20th century when many states were deregulating energy generation to increase competition in the marketplace. The organization grew rapidly in the US market through the acquisition of many smaller utilities that were both publicly and privately owned. Today, Tracks Energy services millions of customers through thousands of miles of natural gas pipelines and electricity circuits that date back to the early 19th century. Tracks Energy is responsible for maintaining existing networks, expanding network capacity, and restoring service outages caused by equipment failures, accidents, and natural events.

1.2 Overview of Electricity Grids

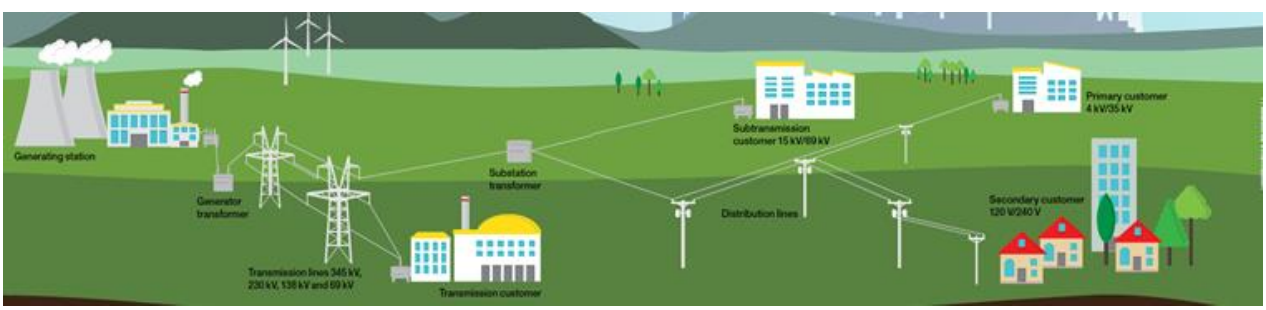


Figure 1 – Typical U.S. Electricity Grid (Tracks Energy, 2012)

We believe that it is important to understand the role Tracks Energy fulfills in supplying customers power in order to understand how their supply chain functions. As was previously mentioned, Tracks Energy owns and maintains both transmission and distribution assets for the supply of electricity. Figure 1 above shows a simplified electrical grid, including the three main components of the U.S. electric grid (Electrical grid.2013) which are:

1. **Electricity Generation**: Electricity is created in power stations that use either combustible (coal, natural gas) or noncombustible fuels (water, wind, nuclear). The electricity is then transmitted to local transformers that step up (increase) the voltage in order to transmit electricity over long distances.

2. **Electric Transmission:** Transmission refers to the mass transfer of energy from power plants to substations which will step down (decrease) the voltage prior to entering distribution networks. The transmission network operates at high voltages (110kV and above) in order to minimize the power lost which is proportionate to the distance covered by the transmission lines.

3. **Electric Distribution:** Electricity distribution is the final stage in the electric grid prior to the customer. Voltage is stepped down in substations (typically less than 50KV) before being routed to customers. Service locations typically require one final voltage decrease (120V and 240V are common values in the U.S.) to achieve the required service voltage(s).

1.3 Overview of Natural Gas Grids

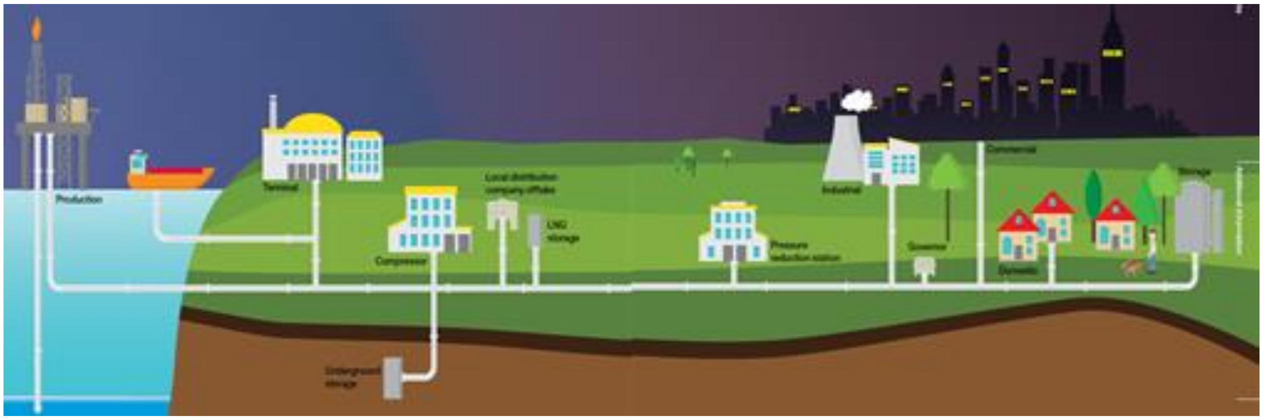


Figure 2 – Example of a Gas Network in the United States (Tracks Energy, 2012)

Similar to their electrical operations, Tracks Energy is focused on the transmission, distribution and storage of natural gas. Natural Gas processing facilities refine the gas to remove impurities as required by customers. The gas is either piped to terminals, or converted to a liquid for efficient storage and transportations (Pipeline transport.2013). There are three major types of transportation pipelines: the gathering system, the interstate pipeline system, and the distribution system (Natural gas.2013).

Gas is transferred from the interstate pipeline system to the distribution system through connections referred to as ‘citygates' (Natural gas.2013). The distribution network operates at low pressures for delivery to customers. In order to maintain system pressure, and to ensure peak demands are satisfied, it is common to store natural gas in a liquid form in storage tanks directly connected to the distribution network. If additional gas is needed to satisfy demand, or needed to maintain pressure, a specified amount of liquid gas will be converted back into a gaseous state and infused into the distribution pipe network.

Distribution networks contain a variety of pipe sizes and materials. Steel and cast iron materials are commonly being replaced with polyethylene pipes to minimize service leaks and interruption (Peoples Gas,). A large portion of the natural gas related work at Tracks Energy consisted of replacing steel and iron pipe with polyethylene pipe.

1.4 Project Background

Rapid acquisitions in both the electric and natural gas sides of the business, without having a well-established parent company, have resulted in operational practices that vary by region. The policies and procedures used to conduct daily activities are heavily influenced by legacy policies and procedures from the acquired utilities. Regional operating practices have created a disconnected platform that has made it extremely difficult for Tracks Energy to launch companywide continuous improvement activities.

Tracks Energy is embarking on a journey to become a process-based organization focusing on standardization and customer satisfaction. Supply chain management of capital and consumable materials is one of the key processes Tracks Energy would like to streamline and dramatically improve over the next three years. The organizational structure is based on technical expertise, and does not include a supply chain management group. A preliminary analysis of supply chain performance revealed a consistent pattern of local optimization decisions made by operational groups which negatively impacted the performance of the supply chain both in terms of cost and service.

This thesis is based on a project between the author and Tracks Energy which was designed to look at the supply chain from a system wide perspective. The scope of the project was limited to the materials that are either installed, capital materials, or materials consumed during installations processes, consumable materials. For the remainder of this thesis, the term "supply chain" will refer exclusively to the procurement and fulfillment of capital and consumable materials. There were four primary goals of this thesis:

1. Development of process maps that reflect current practices relative to supply chain operations
2. Creation of a complexity matrix of strategic supply chain process improvements with projected savings
3. Formation of a scorecard to defined baseline stakeholder performance
4. Development of a strategic inventory model to serve as the foundation for developing inventory policies

1.5 Contributions of this Thesis

This thesis has three primary goals for contributing to supply chain research: A methodology for developing a strategic roadmap of improvement opportunities, applying a simple strategic inventory policy model to guide future process improvements, and the development of a robust optimization inventory model to highlight the usefulness of unfavorable demand scenario planning.

The first outcome of this thesis is a framework for beginning to look at a supply chain as a complete process. Much of the literature surrounding supply chain management and supply chain modeling assumes that standard defined policies are in place, and thus can be improved upon. The literature has also focused on external organizational interactions, however this research assumes that internal process are stable and well defined. In our study, supply chain policies and procedures were not well defined across the organization, and thus looking at value propositions with external organizations was of secondary importance. We propose an approach that uses process mapping, industry benchmarking, and scorecard development in order to develop a foundation for future improvements.

The second contribution of this thesis is regarding the application of a simple inventory policy model designed to minimize ordering and holding costs in the supply chain network. The model as we present it is not new to the literature, but we focus on the practical implications for an organization to evaluate their current ordering and fulfillment processes.

Finally we present a robust optimization formulation with transfers that was developed based on the robust optimization framework. The model we developed provides a practical boundary for unfavorable demand scenario planning, which is particularly applicable to industries where service level is more important than optimizing for cost.

We present the contributions of this thesis as a viable framework for companies and individuals in the early stages of supply chain management and optimization to develop a strategic plan for process and financial improvement.

Chapter 2: Literature Review

2.1 Defining Supply Chain and Supply Chain Management

Many authors have proposed a definition for the term "supply chain", and these definitions consider a variety of different scopes for the term. Some authors have defined supply chains as the processes required to convert raw materials into finished goods (Pienaar, 2009). Others have included an extended view of a supply chain to include information flows and other activities (Ayers, 2000; Chow, D., & Heaver, T., 1999; Mentzer et al., 2001). All of these definitions have their most relevant applications, however it is not possible to apply all of them to every supply chain. For this thesis we will define a supply chain as the organization's network involved in the diverse processes and activities that generate value in the hands of the end consumer (Christopher M., 1998). We recognize the flow of raw materials to distributors is an important aspect of many supply chains, however in this thesis we focus only on internal business organizations at Tracks Energy.

A range of perspectives on supply chain management exist from diverse areas like production and operations management, organizational arrangements, and information technology. We will limit our focus to the emerging area of practice known as construction supply chain management (CSCM) (O'Brien, 2009). The nature of the work accomplished by Tracks Energy is concerned with delivering specific materials in specific quantities to specific projects. The variability of projects executed by Tracks Energy aligns itself with CSCM rather than traditional supply chain management practices engaged by manufacturing firms. In Figure 3 below, we present a framework from O'Brien (O'Brien, 2009) for comparing manufacturing supply chains against construction supply chains. We highlighted the characteristics of Tracks Energy's that are directly applicable to this thesis using bold face type.

Characteristics	Manufacturing SCs	Construction SCs
Structure	Highly consolidated	**Highly fragmented**
	High barriers to entry	Low barriers to entry
	Fixed locations	**Transient locations**
	High interdependency	**Low interdependency**
	Predominantly global markets	**Predominantly local markets**
Information Flow	Highly integrated	**Recreated several times between trades**
	Highly shared	**Lack of sharing across firms**
	Fast	**Slow**
	SCM Tools	**Lack of IT tools to support SC**
Collaboration	Long-term relationships	**Adversarial practices**
	Shared benefits, incentives	
Product Demand	Very uncertain	**Less uncertain**
Production Variability	Highly automated - Lower variability	**Labor availability, productivity, tools - Higher variability**
Buffering	Inventory models	**Inventory on site**
Capacity Planning	Aggregate planning	**Independent planning**
	Optimization models	**Infinite capacity assumptions**
		Reactive approach

Figure 3 – Manufacturing Supply Chains vs. Construction Supply Chains

In order to ensure we focused our efforts on correcting the basic supply chain deficiencies, we relied on research of commonly observed supply chain pitfalls shown in Figure 4 below (Lee & Billington, 1992).

Pitfalls	Symptoms
No supply chain metrics	Independent and disconnected individual sites Incomplete metrics Performance measures not tracked No attention to measures tracked
Inadequate definition of customer service	Inadequacy of line-item fill rate measure No measures for response times No measures for lateness No measures for backorder profile
Inaccurate delivery status data	Delays in providing delivery information Inaccurate delivery information
Inefficient information systems	Inadequate linkage among databases at different sites Proliferation of operations systems for the same function at different sites Delays and inaccuracies of data transfer
Ignoring the impact of uncertainties	No documentation or tracking of key sources of uncertainties Partial information on sources of uncertainty
Simplistic inventory stocking policies	Stocking policies independent of magnitudes of uncertainties Static stocking policies Generic and subjective stocking policies
Discrimination against internal customers	No service measures of internal customers Low priority for internal orders Inappropriate incentive systems Jockeying for priority among different internal divisions
Poor coordination	No coordination among supply divisions to complete an order No system information among multiple supplying divisions Independent shipment plans
Incomplete shipment methods analysis	No consideration of inventory and response time effects
Incorrect assessment of inventory costs	Omission of obsolescence and cost of rework No quantitative basis for inventory holding cost assessments
Organizational barriers	Independent performance measures and incentive systems at different sites Barriers between manufacturing and distribution
Product-process design without supply chain consideration	No consideration of manufacturing and distribution in product-process design No consideration in design for customization and localization Organizational barriers between design and the supply chain
Separation of supply chain design from operational decisions	Chain decisions without consideration if inventory and response time efficiencies
Incomplete supply chain	Focus on internal operations only Inadequate understanding of operational environment and needs of immediate and ultimate customers

Figure 4 – Pitfalls of Supply Chain Inventory Management and their Symptoms (Lee & Billington, 1992)

The information presented in this thesis will build off of the CSCM framework (O'Brien, 2009), and will focus on the intraorganizational relationships between supply chain stakeholders. The work of Lee & Billington (1992) is used as a guide to ensure our strategic road map for Tracks Energy is tailored to their specific needs and deficiencies.

2.2 Scorecard and Metric Tracking

Identifying and using metrics is not a new concept, and many individuals have developed and proposed numerous performance tracking and scorecard formulations. Behn (2003) offers a comprehensive list for why managers would want to monitor metrics: evaluate, control, budget, motivate, promote, celebrate, learn, and improve. In this section we will review some of the more popular and structured metrics and scorecard models before discussing few other less common theories that are more applicable to our project.

The balanced scorecard has become a strategic tool for many large corporations since its development by Kaplan and Norton (Kaplan & Norton, 1992). The balanced scorecard proposes a system that looks across the following perspectives:

1. Customer Perspective (How do customers see us?)
2. Internal Perspective (What must we excel at?)
3. Innovation and Learning Perspective (Can we continue to improve and create value?)
4. Financial Perspective (How do we look to shareholders?)

The intent of this scorecard is to encourage organizations to measure factors that influence financial results. A few critical measures should be developed for each of the four perspectives in order to have a select set of metrics that give a view of an organization's performance from multiple perspectives. The nature of these perspectives lend themselves well to scorecards for senior managers, however, they are somewhat broad for tactical operations focusing on a specific aspect of a business.

A popular scorecard model specifically developed for tracking supply chains, at a tactical and strategic level, was created by the Supply Chain Council. The Supply Chain Operations Reference (SCOR) scorecard was developed in an effort to standardize the measurement of supply chain performance. Since the development of the SCOR model in 1996, it has provided a unique framework that links performance metrics, processes, best practices, and people into a unified structure. This model for performance tracking uses 150 key indicators for measuring supply chain operations, in addition to over 430 executable practices based on the experiences of the Council's membership. Today, several thousand companies utilize a version of the SCOR model (Supply Chain Council, 2012).

Lapide (2006) argues that metrics for tracking supply chain performance is not a one size fits all target. As a part of the MIT SC2020 project, Lapide suggests supply chain owners select relevant metrics based on their ability to satisfy the following four objectives:

1. Supports, Enhances, and is an integral part of a company's competitive business strategy
2. Leverages a supply chain operating model to sustain a competitive edge
3. Executes well against a balanced set of competitive operational performance objectives
4. Focuses on a limited number of tailored business practices that reinforce each other to support the operating model and best achieve the operational objectives

Another framework, including specific metrics, for supply chain performance and measurement based on a functional hierarchy of strategic, tactical, and operational levels is offered by Gunasekaran et al. (2004). The validity of his proposed measurements was supported by conclusions drawn by the authors analyzing 21 customer surveys returned by supply chain intensive firms.

Doran (1981) suggests a framework for metric development similar to Lapide, and offers five characteristics for a good metric for any scorecard. Doran argues that metrics should be specific, measurable, actionable, relevant, and timely to be effective scorecard candidates. Yves (2003) offers a similar point of view by identifying a list of common mistakes regarding metric selection.

1. Metrics for the sake of metrics (not aligned)
2. Too many metrics (no action)
3. Metrics not driving the intended action
4. Lack of follow up
5. No record of methodology
6. No benchmark
7. Underestimation of the data extraction

Doran's characteristics focus on the tactical characteristics of a metric, and Yves' conclusions support the idea of carefully selecting metrics to have a desired strategic intent. Together, these two authors provide a foundation for decision making regarding metric selection.

Finally, Sauder and Morris (2008) make an argument that simpler is better when selecting metrics. They argue that the SCOR model has too many metrics to be relevant for managers to realistically track and act upon.

In this thesis, we will apply the frameworks of Lapide, Doran, and Yves in order to develop a useful scorecard of metrics that is both insightful and actionable by the supply chain stakeholders at Tracks Energy.

2.3 Inventory Modeling

Inventory management represents a significant cost for many organizations, and optimal ordering policies have been widely researched and published in the literature. We will present one of the classical approaches assuming demand and lead time follow the Normal Distribution (Silver, Pyke, & Peterson, 1998). The intent of these assumptions is to provide simple algorithms to minimize cost given desired service levels.

The academic community has been divided as to the accuracy of this approach, since the normality assumption allows demand to be negative when the coefficient of variation is large, or demand volume per period is small (Tyworth & O'Neill, 1997). Tyworth & O'Neill (1997) also note that inventory policies based on normal random variables tend to underestimate reorder points for a given service level. Despite the notable criticism, other authors have been able to mathematically show the choice of underlying distribution has little impact as to the accuracy of the inventory policies based on normal random variables for demand and lead time for single tier (s,Q) supply chain models (Fortuin, 1980). We present our model as a strategic tool which offers insight into cost savings associated with developing inventory policies that are more complex than the ones currently used by Tracks Energy.

We will also present a more complex model, without distribution assumptions, designed to minimize the cost of inventory given unfavorable demand over a discrete horizon. The model we will present is adapted from a robust model, worst case analysis with bounded demand. The formulation of our model will expand on a robust model developed by Bertsimas and Thiele (2006) by including transshipments. We seek to analyze the opportunity of transferring material from one CDC to another in order to minimize costs, known in the literature as transshipments (Paterson, Kiesmüller, Teunter, & Glazebrook, 2011). The literature focuses on quantifying cost avoidance by pooling demand through the use of transfers. Two major areas of interest in the literature are economic transshipments and emergency transshipments.

Given the current regulatory restrictions imposed on Tracks Energy, we will focus on the use of economic transshipments in our model. Research done by Herer and Tzur (2001), and Herer et al. (2003) have studied transfers in a deterministic demand setting. We will study economic transshipments through a robust approach assuming uncertain demand.

Emergency transshipments are only considered when a warehouse experiences a stock out condition. Stochastic optimization has been used by some researchers to try and minimize long term average inventory costs (Axsäter, 1990; Axsater, 2003; Kukreja, Schmidt, & Miller, 2001). These authors present approximations to simplify the complexity of independence of demand between warehouses so that tractable optimization methods could be used. Tracks Energy currently executes emergency transshipments, however the complexity of these models is not the appropriate first step for increasing the sophistication of inventory policies currently used by Tracks Energy.

One of the concerns with robust optimization is its tendency to develop overly conservative solutions. An approach designed to mitigate this problem is offered by Ben-Tal, Bertimas, and Brown (2010) called "soft robustness". In their approach they allow feasibility guarantees to vary across uncertainty sets which allows the level of optimality to be an output of their formulation. In this thesis we will present a more traditional robust formulation, however we acknowledge the opportunity to potentially improve our model by taking a more conservative approach.

2.4 Chapter Summary

In this section we presented a variety of relevant works for supply chain management, metrics development, and inventory modeling. We identified the frameworks that lend themselves well to our particular application. We will build upon those frameworks using specific information from our experience at Tracks Energy.

Chapter 3: Organizational Analysis

3.1 Three Perspectives of Organizational Processes

We believe that a person must understand the organization they are working in before it is possible to begin offering a strategic vision for future processes. The faculty at the Massachusetts Institute of Technology Sloan School of Management teach the idea that "Perspectives are organized ideas (e.g., metaphors) that fundamentally shape our understanding of things and events" (Van Maanen, 2008). Analyzing an organization from multiple perspectives will provide a foundation for developing a value vs. complexity framework with which to evaluate opportunities. In some organizations it may be easy to modify the way interactions between functional groups occur; however in other organizations it may be extremely difficult. Understanding the complexity associated with each opportunity is critical to understanding the actual cost (tangible and intangible) associated with pursuing an initiative. For this project, we analyzed Tracks Energy through three different perspectives:

Strategic Lens: The strategic lens looks at an organization as a mechanical system that is designed to accomplish specific tasks. In particular, this lens looks at how the structure of the organization enables it to accomplish the defined goals of the organization.

Cultural Lens: The cultural lens looks at an organization as an institution symbolic of values, routines, traditions, and behavior. This lens looks at achievements as the result of habits, rather than organizational design.

Political Lens: The political lens looks at the organization as a social system that empowers individuals to accomplish specific goals. The goals of individuals can be contradictory between each other, and also contradictory to the goals of the organization. This lens looks at how the power distribution in the organization is achieved, and how it impacts what gets accomplished.

3.2 Strategic Design Lens

For the purposes of this document we will limit the analysis of the organization to the departments and individuals directly associated with supply chain operations. Performance of the Tracks Energy supply chain is not the responsibility of one department, but rather the combined efforts of ten distinct groups reporting up through a structure spanning four different executive managers.

Since Tracks Energy is a regulated utility, it relies on the respective state and federal regulators to approve the rates charged to customers, and their requested rate of return on assets over a specified period of time. There are several publications relative to how public utility rates are established, so for more details on the subject we refer the reader to (RAP, 2011) for a comprehensive overview. The goal of the organization is to make money, however income is heavily influenced by regulators who are influenced by the public and elected officials. Figure 5 below shows a commonly perceived circle of influence by Tracks Energy employees, which helps to explain why customer satisfaction is a top priority.

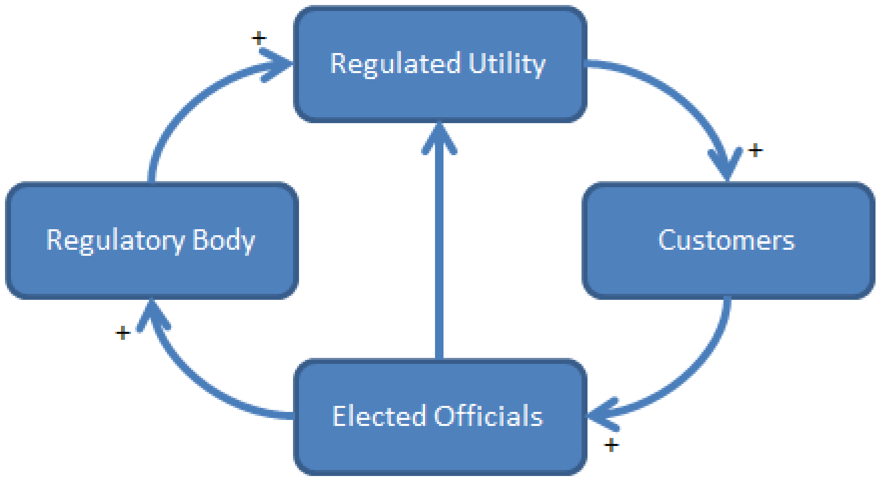


Figure 5 – Perceived Circle of Influence at Tracks Energy

The observed emphasis on customer satisfaction is supported by the role served by the operations performance group. Operations Performance is a team of individuals that compile reports and metrics for review by executive managers. The vast majority of the data this team tracks is related to either safety or customer satisfaction. Only a few sporadic metrics consistently track operational efficiency. The current scorecard supports our perceived circle on influence through the emphasis on customer satisfaction over efficiency. Additionally, historically operational efficiency was done at a local level since many of the acquired utilities that now make up Tracks Energy were very small. Now that the organization has grown, there is a much larger pool for coordinating activities to streamline operations across regions. Several structural changes to the organization over the last several years have also made it challenging to look at global operational efficiency due to individuals changing roles and areas of responsibility.

The overriding priority of the Tracks Energy organization is to provide unparalleled levels of service, safety, and security to its customers. In essence, the organization strives to safely keep the lights on and the gas flowing. There are three main categories of services that Tracks Energy provides:

1. **Emergency Restoration**: Restoring gas and electric services to customers in the event of equipment failures, accidents, or natural events resulting in interruptions of service.
2. **Program Work**: Program work refers to routine planned maintenance to improve the reliability of services being provided to customers. On the electric side of the business, this would include the replacement of equipment approaching service life expectancy, or upgrading equipment whose failure rates have exceeded acceptable levels. On the gas side of the business, this category of work is primarily main pipe replacement.
3. **Project Work:** Project work refers to the complex construction of new assets. On the electric side of the business, this is typically running new transmission or distribution lines, including new substation installations. On the gas side of the business project work includes complicated redesigns of gas mains, or complex expansion of the gas main network to accommodate new customer services.

With a high level understanding of the organization goal, we now turn to the organizational structure designed to accomplish those goals. We will briefly introduce the functional groups here, however the reader should refer to Chapter 4 for more details. Figure 6 below shows the organizational chart for the key individuals who set policies and directives influencing supply chain operations.

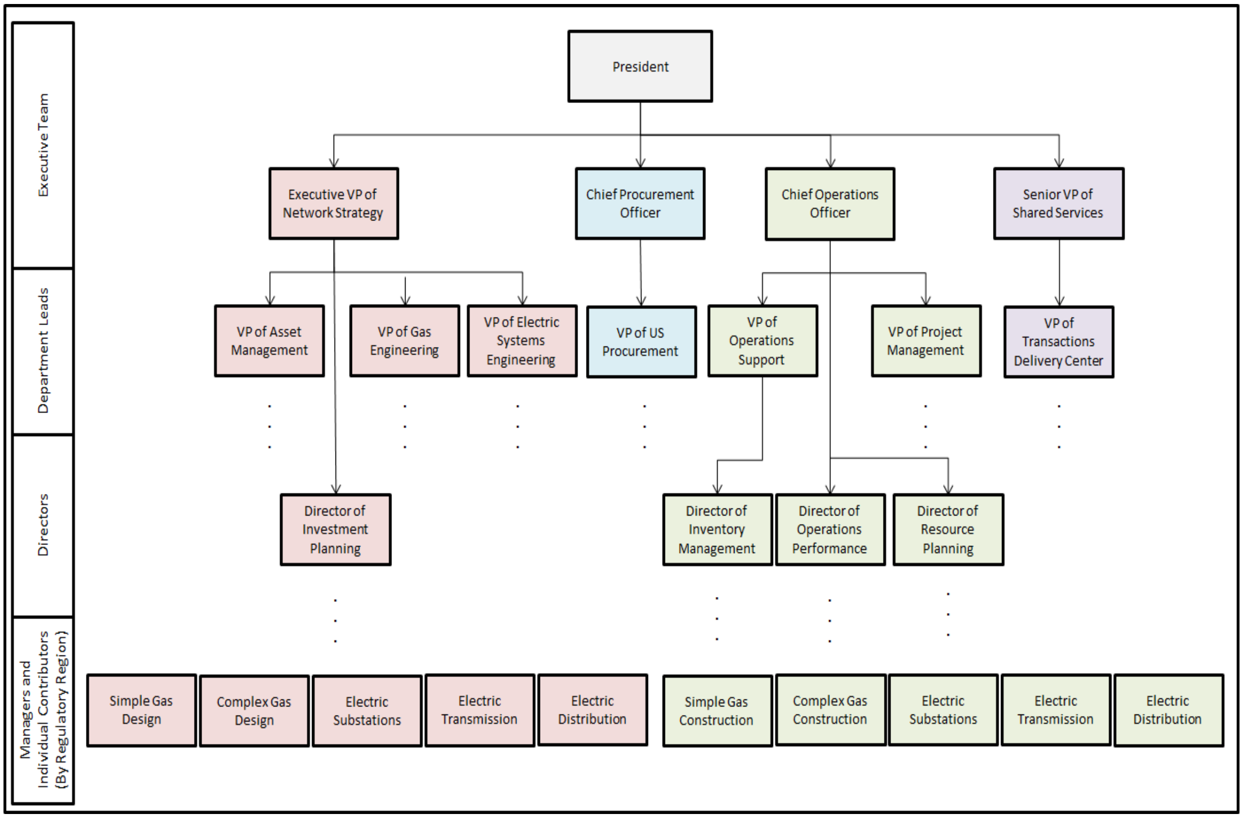


Figure 6 – Tracks Energy Organization Chart for Supply Chain Operations

Investment Planning and Network Strategy: Investment Planning is the group responsible for ensuring long term planning aligns with regulatory priorities for both electric and gas assets. Network Strategy operates using three different planning cycles: 15-year, 5-year, and 1-year. The 15 year plan is primarily ongoing maintenance programs identified by Asset Management with estimated budgets. The 5 year plan includes blanket budgets for project and program work in each regulatory area. As new projects or programs are identified and approved, they are allocated a representative portion of the blanket budgets. The 1 year plan is intended to have details for all known project and program work expected to occur over the next fiscal year, in addition to blanket budgets for emergent work that is expected to develop within the 1 year planning cycle.

Asset Management: Asset Management develops work plans to manage lifecycles for company assets. This group develops and supports capital and maintenance plans for electric transmission and distribution, gas operations, and electric and gas engineering. Equipment failure rates, Smart Grid requirements, and equipment service life are all common inputs into this group's planning process.

Engineering: The engineering team is divided by regulatory region and functional expertise: electric transmission, electric distribution, electric substations, gas transmission, and gas distribution. Engineering is responsible for the design and resource management of services. Electric circuit engineers are responsible for submitting bill of material (BOL) requirements for all project and program work. Gas engineers are only responsible for submitting BOLs to order custom materials. Gas work crews order standard materials from regional centralized distribution centers (CDCs) as required.

Resource Planning: Resource planning is responsible for executing the 1 year plan developed by Network Strategy. This group affords visibility of the annual work plan, in addition to the progress against it. Resource planners attempt to optimize asset and resource decisions within each regulatory area in accordance with rate plan allowances.

Procurement: The procurement team fills the role of a strategic procurement group. Procurement is expected to proactively identify business needs while reducing sourcing costs. These individuals are responsible for ensuring contracts and procedures are in place for the acquisition of any materials or services that any business group may require.

Transactions Delivery Center (TDC): The TDC has two primary functions in the supply chain. The first is to create POs and submit orders to vendors on behalf of the engineering and inventory management groups, more commonly known as tactical procurement. The second primary function is invoice processing including vendor payment.

Inventory Management: Inventory management's primary function is warehousing and distribution of materials required for the construction and maintenance of assets. Inventory management is responsible for capital equipment as well as consumables (e.g. safety glasses, gloves, safety cones, etc.).

Operations: The operations teams execute the work assigned to them by the Resource Management Group. We use this term broadly to describe the role of many different individuals in the organization, without preoccupying ourselves with the exact details of how each group executes their work. Project work is primarily performed by contractors who were awarded the work based on a bidding process conducted by procurement. Tracks Energy crews perform the majority of the program work in addition to responding to outages (emergency restoration). In the event of a storm that results in large numbers of service outages, all Tracks Energy and contract crews will be reassigned to restoration efforts. Severe storm restoration is frequently supported by contract crews sourced from areas unaffected by the storm.

Program and Project work are typically planned and executed by regional project teams spanning across organizational groups, introducing a matrix structure to the organization shown in Figure 6. Project/Program leads are typically managers, or individual contributors within one of the functional silos. For example, a project team for an electric distribution line project would contain individuals from different departments who exclusively specialize in electric distribution line work in a specific regulatory region. The project lead does not typically have authority over individual contributors to hold them accountable for project expectations. This matrix structure blurs accountability for project cost and schedule performance, and does not provide incentives for individuals to look beyond their immediate responsibilities.

Decisions surrounding how work gets completed, documented, and what tools are to be used are made at the director level in each of the state regulatory regions. During interviews with employees to understand how the supply chain functioned, we learned that each area of expertise in each regulatory area used different software and procedures to accomplish their tasks. Functional silos further divided into regional silos are the downside to this organizational structure. Best practices identified in a particular regulatory region or areas of expertise seldom permeate throughout the organization.

The strength of this organizational structure is in reacting to emergencies and natural disasters that interrupt services. Highly specialized individuals are able to be reassigned from project and program responsibilities to restoration activities. The speed and efficiency of restoration activities during interruptions can have a significant influence regarding customer service ratings and expense recovery. The speed and efficiency of restoration activities can also have significant financial impacts to utility companies. New Jersey Governor, Chris Christie, has introduced legislations that would increase fines charged to utility companies from $100/day to $25,000/day for slow storm responsiveness (Caroom, September 6, 2012). Fines levied against utility companies are not passed onto customers, which emphasizes the need for utility companies to react quickly to restore service.

The regional and functional silos in the organizational structure encourage managers and individual contributors to look at their individual tasks, without worrying about how their decisions impact other groups. The initiatives developed for our proposed strategic roadmap will incorporate both tangible and intangible costs associated with aligning incentives across functional silos.

3.3 Cultural Lens

Tracks Energy is still working to define its corporate culture. Because Tracks Energy's growth has been by acquisition, its culture is a conglomeration of nuances from smaller electric and gas utilities. The electric utilities acquired prior to 2007 are commonly referred to as legacy Tracks, and gas utilities acquired in 2007 are referred to as Acme Pipe and Gas. Acme was the last major acquisition for Tracks Energy, and represents the vast majority of natural gas services under the Tracks Energy umbrella. It is common for employees to refer to the electric side of the business as Tracks Energy, and the gas side of the business as Acme, even though the merger occurred 5 years ago. While these designations seem superficial, they are a clear indication of the functional and cultural silos that exist between the gas and electric sides of the business. During interviews we conducted with gas employees, many of them stated that they can't learn anything from the electric side of the business because gas work is heavily standardized with few requirements for special one off materials. Likewise, interviews with electric employees confirmed that they also feel that they have nothing to learn from the gas side of the business. The perceived functional silos outlined in the previous section are further supported by cultural nuances.

Another important cultural nuance at Tracks Energy is the level of mistrust between the field crews and central office supply chain functions. The expansion through acquisition growth that Tracks Energy has experienced has resulted in people working in an organization much larger than they are used to. In many cases, the field crews have years of experience in much smaller organizations, and are not experienced working in an organization with large centralized procurement and inventory management functions. For many of them, all of their materials were stored locally and directly accessible to them. When inventory on the shelves of the crew barns ran low, the crews were at risk of not having the material they needed. Tracks Energy now uses a regional distribution center model to reduce the amount of redundant material throughout the network. Even though each yard receives material multiple times per week using standard milk runs from the distribution centers, the field crews do not yet fully trust the distribution system. When the field crews see low inventory, their instincts tell them that they need to order enough material to refill the shelves. The concept the field crews frequently fail to grasp is that the lead time for ordering materials is now as little as a few hours, instead of one or two weeks. This creates a propensity for field crews to order more material than they actually need to conduct their daily activities.

Conversely, the centralized inventory management and procurement individuals are able to see the total amount of inventory stored at the distribution centers, and attempt to forecast their orders based on historical orders from crew barns. Each time a crew barn orders excess material, it inflates the demand perceived by procurement and inventory management, which inflates the amount of material ordered from suppliers. When the employees performing the centralized inventory procurement and management functions visit crew yards, they see excess inventory on the shelves. This creates doubt in the minds of inventory management and procurement personnel that the crew yards actually need all of the materials they are ordering. This situation creates the potential for inventory management to become desensitized regarding stock outs because they believe ample material is still available at the crew yards. At the same time, the situation creates the potential for field crews to become over sensitized to stock outs.

The scope of this project was designed to align the supply chains for gas and electric operations into a single supply chain model. For the Chief Procurement Officer, the executive project sponsor, this project is intended to get the electric and gas supply chain stakeholders to work together to standardize the way the business operates.

The strategic roadmap outlined in this paper will be sensitive to the cultural nuisances of Tracks Energy when evaluating the complexity associated with specific improvement initiatives.

3.4 Political Lens

Every March, the Tracks Energy executive team develops a list of initiatives that will be pursued over the following fiscal year. Some initiatives are department specific, while others are intended for broad corporate influence. The specific initiatives are not relevant for our analysis, however the ownership and importance to the organization of the initiatives is. We used this perspective to understand how people in the organization are empowered and incentivized.

Power in the organization is developed, in part, by a person’s title. Employees seemed to be astutely aware of expected promotions once director and vice president level positions became open. The employee that was perceived as the front runner was consulted more often than others by peers. Upon further investigation, we learned that employees actively try to connect themselves with high potential individuals in hopes of accelerating their career growth.

The owner of the supply chain management initiative we supported was the Chief Procurement Officer. His ownership means that part of his, and his team's, annual reviews will include goals and accomplishments relating to supply chain improvements. In addition to the supply chain management initiative, the procurement department was also trying to decrease sourcing costs, and increase the amount of materials sourced from low cost countries when they could reduce total expenditures. During annual reviews, procurement employees will have to demonstrate how they supported both of these initiatives.

Success of the supply chain management will require a significant amount of support from executive managers other than the Chief Procurement Officer. Unfortunately, the other members of the executive team have their own initiatives they are responsible for, and thus incentives across the organization are not necessarily aligned. The proposed supply chain scorecard will be a key strategic tool designed to align incentives and balance power, related to supply chain operations, across the organization.

3.5 Chapter Summary

In this chapter we reviewed aspects of the Tracks Energy organization through a three lens analysis taught at the MIT Sloan School of Management. The strategic analysis provided insight into how the physical structure of the organization is designed to accomplish the goals of the organization. The cultural analysis provided insight into the soft aspects of the organization which will need to be considered. Finally, the political analysis provided insight into the way power and decision practices can be used to garner support for our recommendations.

Chapter 4: Analysis of Current State Supply Chain Operations

In order to develop a strategic roadmap for improvement, we believe it is necessary to understand the starting point. Trying to copy the actions of others without truly understanding the current state of the processes and procedures of an organization is a recipe for failure. Perhaps the most obvious example of this practice is the failure of many manufacturing companies to successfully implement the Toyota

Production System (TPS). All of the domestic automakers have spent considerable time and effort to align their strategic plans with the processes included in the TPS. Despite their best efforts, their strategic roadmaps led them to financial distress. The TPS is more than a group of processes designed to efficiently build vehicles, it is also an underlying philosophy on which the processes are developed. In this section we will show how the use of process mapping techniques, data analysis, and benchmarking are critical tasks required to develop a viable strategic roadmap based on existing company philosophies and practices.

4.1 Supply Chain Overview

In Chapter 3 we introduced the three main categories of work the Tracks Energy supply chain supports: project work, program work, and emergency restoration. In this chapter, we further classify the work as planned and unplanned work. Project and program work are part of the annual planning process and thus can be considered together as planned work. Lead times for planned work vary from one month to as long as three years. Unplanned work consists of the random demand for materials due to system and weather related failures. In this section we will present our approach to process mapping, and the supply chain implications of the planned and unplanned work of the supply chain.

Since this study represents the first attempt by Tracks Energy to look at the supply chain from an end to end perspective, our focus was on the two primary tiers of the supply chain. The first tier represents the movement of material from suppliers to centralized distribution centers (CDCs), and the second tier represents the movement of material from CDCs to crew yards. Figure 7 below is representative of the flow of both capital and consumable materials for Tracks Energy. Tracks Energy has in excess of 25,000 SKUs in its catalogue, however less than 10,000 of those SKUs generated demand in 2011 and 2012.

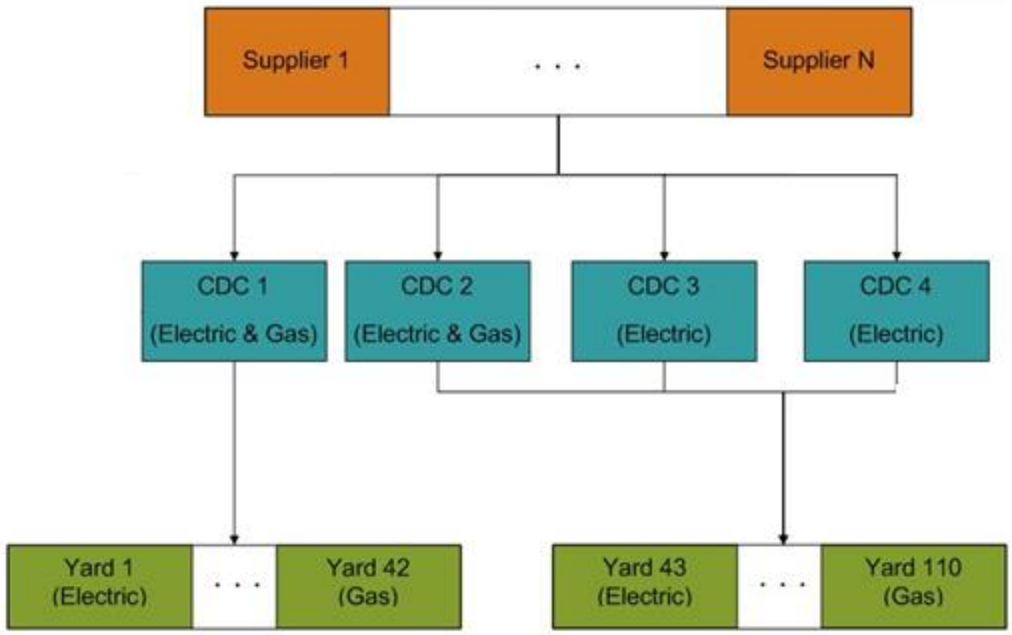


Figure 7 – Tracks Energy Supply Chain

The supplier network for Tracks Energy consists of both direct manufacturing suppliers, and general distributors. To simplify our analysis, we do not concern ourselves with the entire value chain of suppliers, including tier 2 and tier 3 suppliers, and only consider the lead time from companies directly supplying materials to the central distribution centers (CDCs). The four CDCs are regionally located, and are intended to service specific crew yards. Most crew yards are designed to supply exclusively gas or exclusively electric materials to work crews, some yards support both gas and electric crews from a single storage facility. Inventory and demand visibility in the work management systems are restricted only to CDCs, so our analysis does not include individual demand at the crew yard level.

4.2 Process Map Development

Process map development was the first and most important step to developing our strategic roadmap. The opportunities we identified are based on process deficiencies validated with the information we learned through the development of our supply chain process maps. This process also enabled us to identify processes designed to maximize total supply chain utility over individual department goals.

We conducted interviews with supply chain stakeholders to understand their role in supply chain operations, what they considered their process inputs, their process outputs, and the tools they used to accomplish their tasks. The interviewees were both high level managers and individual contributors. With the information from the interviews we were able to identify the key processes in place relating to supply chain operations. We were also able to map information flows and software tools that contained supply chain information. With the information gathered, we were able to develop a detailed process maps for supply chain operations for both planned and unplanned work.

This process was very time consuming, however we learned several key lessons summarized below:

1. The planning process for gas, electric distribution, and electric transmission operations all had subtle differences.
2. A project management playbook had been developed internally by a cross functional group of Tracks Energy employees, however it had not been fully implemented at the time this thesis was written. Once the playbook is fully implemented, it will standardize many of the processes across all planning and operational groups.
3. Software systems used were not able to communicate directly with each other, which siloed information at various stages of the planning and fulfillment processes.
4. Stakeholders frequently believed information transfers were handled by other departments, but they were not, creating broken and inconsistent information flows between departments.
5. Stakeholders all seemed to have a perception of how their work was used by other groups, however they were frequently incorrect.

Figure 8 below is a simplified representation for the process map for planned work. The responsibilities of the ten operational groups involved in the collective operation of the supply chain are presented along with consistent information flows.

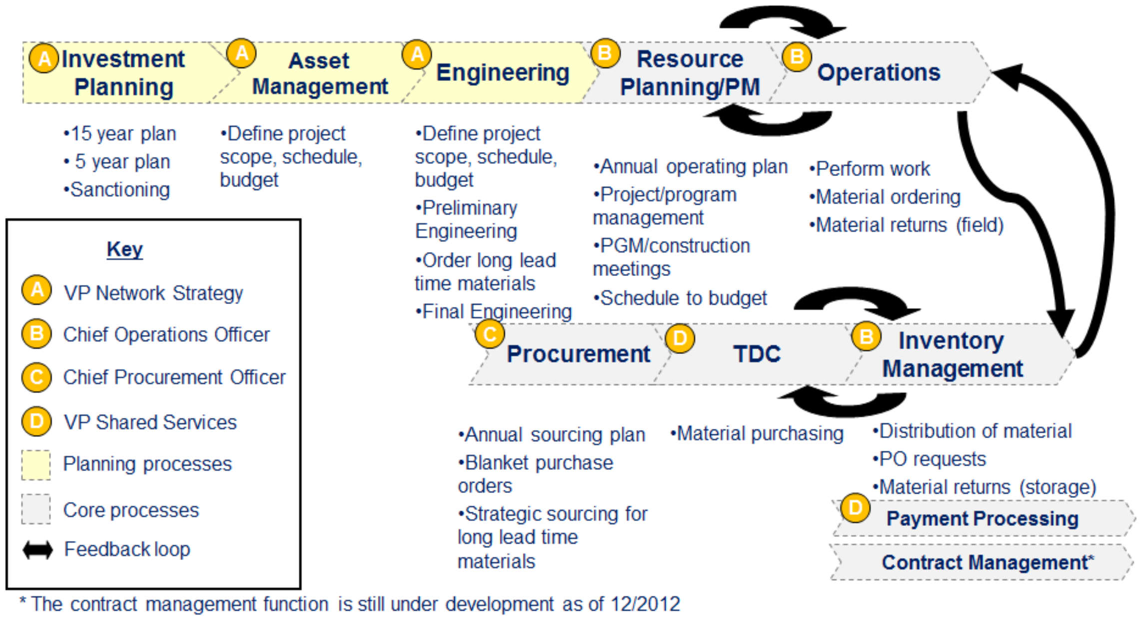


Figure 8 – Tracks Energy Supply Chain Responsibilities

With an understanding of the tasks accomplished by the different departments, we were able to turn our attention to data analysis of performance characteristics. Before we present our analysis in Section 4.5, we present some more background information for the reader's understanding of this particular supply chain.

4.3 Material Fulfillment and Distribution

This section will cover generic material fulfillment and distribution regardless of the demand being generated by planned or unplanned work.

Material planners submit orders for materials to the TDC on behalf of one of the four regionally located CDCs using a process similar to an (s,Q) inventory policy. Orders from the CDCs to suppliers are triggered based on inventory positions with constant reorder point levels respective to each SKU. A daily report is automatically generated by the inventory management software which identifies any materials that have an inventory position below the reorder point. Minimum suggested order quantities are fixed values in the inventory management systems used by the organization. A dynamic economic order quantity (EOQ) is not readily available to the material planners. At some previous point in time an EOQ value was determined and hard coded into the inventory management software. Lead times are also fixed values that can be updated by the material planners based on their observations. Empirical lead times are not automatically calculated, or reported, by the inventory management software. The primary concern of material planners is to make sure material is fulfilled to crew yards prior to a stock out condition occurs. The lack of accurate EOQ values and empirical lead times increase fulfillment costs, and jeopardize the material planner's ability to procure material prior to stock out conditions.

Crew barns are staging locations for work vehicles and materials (capital and consumable). Materials stored at crew barns are not considered inventory, but rather expensed or precapitalized items. Since these items are not considered inventory, they are not electronically visible in any inventory management system. The only way to know the true value of all available materials would be to manually count what is on the shelves and on the trucks at each of the crew barn location simultaneously. The original intent was to have small quantities of inexpensive, or commonly used materials, available to crews without availability being restricted to times when storekeepers were available to perform inventory transactions in the material management system. Over time this concept grew to include large quantities of expensive items like poles, transformers, pipe, and cable. The only items that are considered inventory at crew barns are critical spare units that are not expected to be used except in case of an emergency. The crew barn shelves and bins are replenished using manual heuristics developed by storekeepers who are frequently responsible for multiple crew barns.

4.4 Project/Program Planned Work

Project work refers to the new construction aspects of expanding the network. Examples of this type of work would include installation of new transmission lines to service a new demand area. Likewise, modifying the network for a new manufacturing facility that represents additional demand in the distribution network would also represent project work. Program work primarily refers to maintenance of existing assets. Examples of program work would be battery replacement in substations, transformer replacements corresponding to assets at the end of their useful life, and other assets that may be contributing to unplanned outages.

4.4.1 Project and Program Work Planning

Tracks Energy does not have a comprehensive planning process for supply chain management. In October of each year, the Investment Planning, Asset Management, Engineering, and Resource planning groups get together to massage a preliminary annual plan proposed by Investment Planning. The initial proposal, adapted from the corresponding 5 year plan, does not account for resource availability. During interviews with these four groups, we learned that it was common for the 5 year plans to be incompatible with crew resources across the regulatory regions. The result of the combined effort of these groups becomes the active annual plan, and Resource Planning becomes the owner of execution to plan.

While the annual construction and maintenance plan is being developed, the procurement team is independently developing their sourcing plan. Procurement primarily relies on historical usages for their estimates of material requirements. Informal communications between procurement team members and the groups involved in the construction annual plan occur sporadically, and do not have a significant influence over Procurement's annual sourcing plan. The Procurement group works with suppliers to create sourcing contracts based on their estimates for usages over the following year. Any gaps in sourcing plans are corrected by sourcing events that are conducted by the Procurement department throughout the year. Prior to 2011 these sourcing events were not documented, which prevented the ability to correct planning deficiencies year over year. Actual procurement of materials is the responsibility of the TDC, who generates POs according to the sourcing contracts once orders are submitted by inventory management or engineering.

Communication between inventory management and the annual project planning teams is not well defined, which prevents any systematic improvements for material planning in the warehouses or crew barns based on forecasts. Inventory management planning is based on lessons learned in previous years, without input from current planning cycles.

Throughout the year, Resource Planning conducts monthly construction meetings that review progress to plan. In these meetings, the actual start dates of projects and programs are updated based on resource constraints and shifting project and program priorities. These meetings include representatives from Investment Planning, Asset Management, Engineering, and Operations. Inventory Management and Procurement do not attend these meetings.

4.4.2 Material Procurement and Distribution Activities for Planned Work

This section will focus on the tactical execution of supply chain activities as they relate to planned work. We will present the decision points that trigger material procurement and distribution.

Planned demand is triggered in one of two ways:

1) Electrical Engineers develop BOM requirements for projects and input project need by dates to trigger material delivery to crew yards.
2) Work crews order gas materials that are required for construction since gas engineers do not submit bill of materials (BOMs) for design plans.

During the *preliminary engineering phase* of design for project and program work, electrical engineers develop preliminary BOMs that represent their best estimate for material requirements. These preliminary BOMs are visible to the Inventory Management group through inventory management software, but will not trigger demand until the final engineering phase is complete. Custom order materials are submitted to the procurement department which will conduct a sourcing event with potential suppliers. Custom order gas materials are also ordered during the preliminary engineering phase, however gas engineers do not develop comprehensive BOMs.

During the final engineering phase, electrical engineers finalize the BOMs and submit material need by dates to inventory management through the inventory management software. SKUs included in the final engineering BOMs with due dates in the next 120 days are considered imminent demand, and are counted against the inventory positions for those SKUs. Actual project and program start dates, which fluctuate during construction meetings, are only updated in the project management software tools. The project management software does not communicate with the inventory management system, so inventory management is not aware of the changes to material need by dates.

In the event that the BOMs submitted are not complete, work crews will pull material from reserves located at the crew yards, or they will order the material directly from the CDCs. This demand will appear as random demand even through it should have been included in the original design. The accuracy of BOMs is not tracked, and thus feedback to engineering for continuous improvement activities is nonexistent.

Electric project and program materials are intended to arrive to crew barns based on the material need by dates entered by engineers in the final engineering stage of design. These materials are intended to be kept in designated storage areas so work crews can gather all of the materials they need for a job in one location.

Gas project and program materials are commonly ordered by work crews 1-2 weeks before construction is anticipated to begin. Standard materials are pulled off of the shelves at crew yards when construction begins. The materials that were ordered for that project will then backfill the materials taken off of the shelves.

4.4.3 Planned Project and Program Work Reverse Logistics

Materials not used by contractors and Tracks Energy crews are supposed to be returned to crew yards or CDCs for use on future jobs. Materials in their original packaging can be returned to the CDC for credit to the project the materials were originally expensed to or capitalized against. Partial packs cannot be returned to CDCs for credit, and will either be stored at the crew barn, held in contractor yards, or given to an investment recovery group for salvage disposition. The investment recovery group will process the materials returned in one of the following four ways:

1) **Repackaging**: Recreate standard pack quantities to be returned to CDCs for redistribution into the network.
2) **Liquidation**: Sell items on the open market to recover a portion of the original material value.
3) **Salvage**: Sell material to scrap firms for minimal return on investment.
4) **Dispose**: Dispose of the materials without attempting to recoup any potential salvage value.

The amount of material not used on projects is difficult to track, and thus difficult to drive continuous improvement back into the engineering design phase of projects. The amount of material stored in contractor yards is not monitored, and thus is not included in any estimates of available inventory. Since material in crew barns is not tracked as inventory, it is also not possible to understand the flow of material from the field back into available material.

4.5 Current Performance

Some supply chains are designed to minimize cost for a competitive advantage, and others are designed for responsiveness. It was not clear at Tracks Energy what the correct balance between these two extremes should be. Tracks Energy engaged in this project to reduce costs without jeopardizing their current level of responsiveness. To understand the current balance, we used a combination of data analysis and benchmarking against other utilities in the United States.

Tracks Energy did not have any supply chain specific metrics tracking in place at the beginning of our project with them. A few stakeholders tracked metrics specific to their own operations, but these metrics rarely encompassed both legacy Tracks and Acme performance indicators. In an effort to understand system wide performance, data from legacy Tracks and Acme was used to develop a baseline for performance. Below we present the current performance of the supply chain through metrics representing measures of both cost and responsiveness.

4.5.1 CDC Order Fill Rate

We began our analysis with the CDC order fill rate. Since Tracks Energy does not track inventory or order fulfillment at the crew yard level, we did not have insight into the fill rate to the final customers, the work crews. Our measure indicates only the ability of the CDCs to respond to orders from crew yards. The existing management systems did not allow us to identify planned work orders independently from unplanned work orders.

Order fill rate is an important indicator of responsiveness of the supply chain. It provides us insight into the ability of the supply chain to supply the materials required in the correct quantity. We calculated order fill rate using Equation 1below.

$$CDC\ Order\ Fill\ Rate = \frac{Orders\ Completely\ Filled}{Total\ Orders}$$

Equation 1 – CDC Order Fill Rate

The performance for each CDC was calculated independently, and then aggregated for the performance illustrated in Figure 9 below. We can see that the responsiveness of the CDC network appears to be lagging behind the performance of other utility companies. The CDC Order Fill Rate can be negatively impacted by either not having the correct materials stocked, or not having sufficient quantities of materials in stock. For example, stocking out of a common bolt or a common transformer have the same impact on the order fill rate. It is not clear based on this metric alone that Tracks Energy's supply chain is not responsive to customer requests because fulfillment to final customers is not tracked.

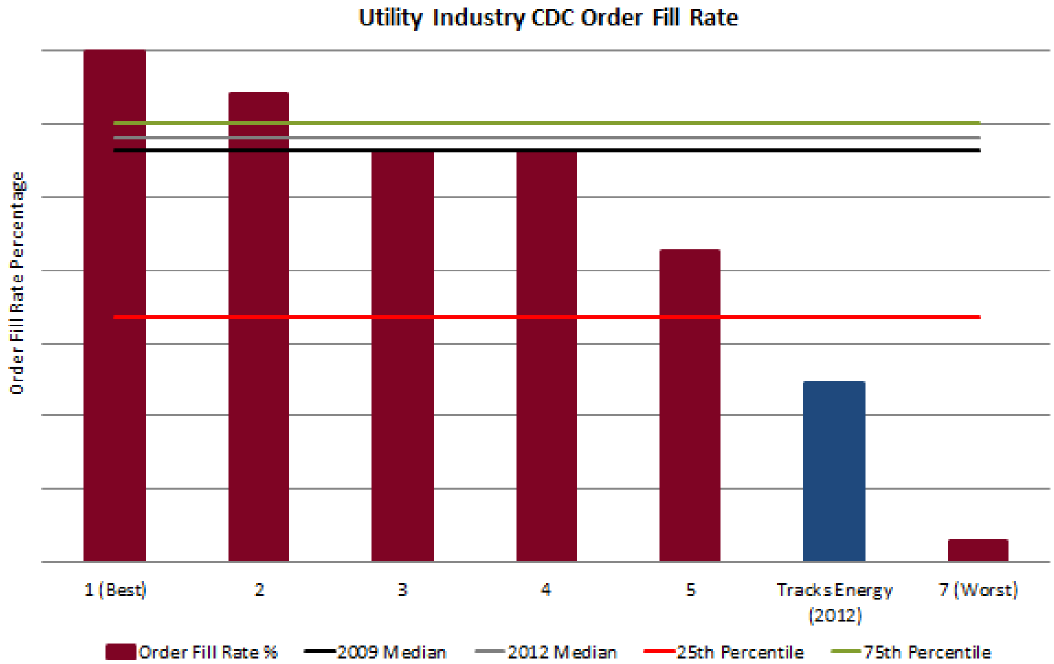


Figure 9 – Tracks Energy CDC Order Fill Rate

4.5.2 CDC Line Fill Rate

An alternative view of response rate is to look at line item fill rate. Line item fill rate is another common supply chain measurement that doesn't look at items in aggregate for an order, but rather only individual line items. Line item fill rate was calculated using Equation 2.

$$CDC\ Line\ Fill\ Rate = \frac{Lines\ Completely\ Filled}{Total\ Lines\ Ordered}$$

Equation 2 – CDC Line Fill Rate

By comparing the line item fill rate to the order fill rate, we were able to clearly see the responsiveness of Tracks Energy is lagging behind other utilities (see Figure 10). We performed a detailed analysis of the raw data for these two metrics in order to ensure we were coming to logical conclusions. The data showed us that both line fill rate and order fill rate were being negatively impacted by both not having the desired materials in stock, or more commonly, only being able to partially fill orders. The goal of this project was to reduce costs without negatively impacting fill rates, however our analysis of these two metrics indicated that there may be an opportunity to improve both cost and responsiveness.

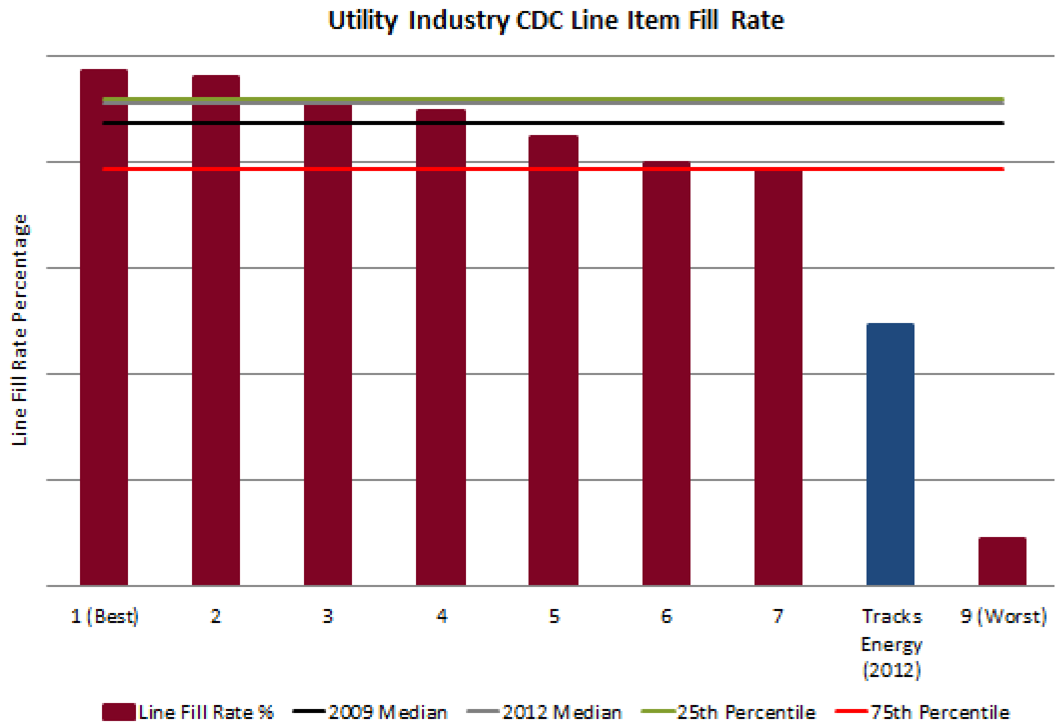


Figure 10 – CDC Line Item Fill Rates

4.5.3 Inventory Turnover

After analyzing fill rates we turned our attention to inventory turnover. Inventory turnover is an indication of how efficiently the supply chain is able to fulfill orders, and replenish inventory. The higher the inventory turnover, the more efficiently capital is being used for inventory investment. Inventory turnover performance varies by industry, but the utility industry in the United States averages two turns per year (Applied Energy Group, 2009).

$$Inventory\ Turnover = \frac{\sum_{SKU=1}^{n} Average\ Unit\ Cost * \ Annual\ Demand}{Average\ Inventory\ Value}$$

Equation 3 – Inventory Turnover

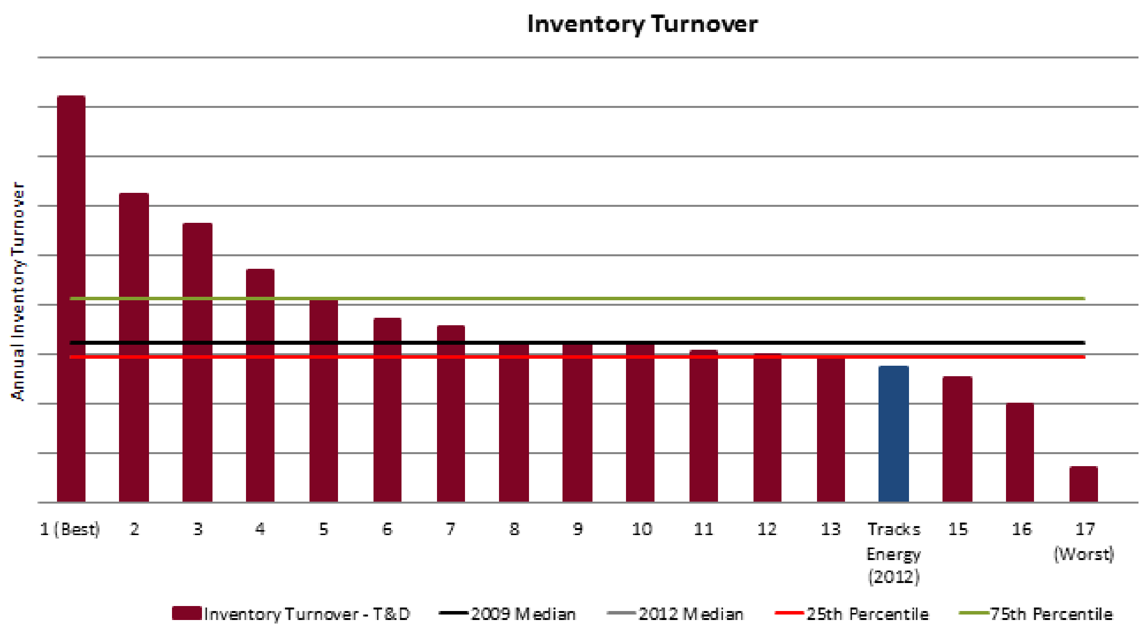


Figure 11 – Inventory Turns for Total Stock (Inventory Safety Stock and Critical Spares)

Figure 11 above shows that Tracks Energy likely has an opportunity to improve the efficient use of capital for inventory expense. It is not possible to directly compare utilities to each other since inventory for each company includes regulated emergency spare equipment. Regions requiring larger quantities of critical spare units due to local regulations can degrade the performance of particular companies. The benchmarking information available did not provide insight into the value of material required by regulatory bodies, and thus could not be used to make a perfect comparison across all utility companies.

Poor performance for this metric can be caused by either stocking too much of the materials commonly used, carrying a large amount of slow moving stock, or a combination of the two. Fill rate metrics indicated that there was an opportunity to improve responsiveness, while inventory turnover indicates there is an opportunity to decrease inventory investment expenses.

4.5.4 Inactive Inventory

One type of inventory that can have a significant impact to inventory turns is inactive inventory. For the purposes of our project, we defined inactive inventory as any materials that didn't have demand in the last two years. We excluded critical spare inventory, regulated inventory required to ensure responsiveness in the event of a natural disaster, from the calculation of this metric. Obsolete/Inactive inventory has the ability to represent significant costs to a firm since warehouse space could be reduced, or reallocated for active materials. Inactive inventory was calculated using Equation 4 below.

$$Inactive\ Inventory\ Percentage = \frac{Inactive\ Inventory\ Value}{Total\ Inventory\ Value}$$

Equation 4 – Inactive Inventory Percentage

Figure 12 below illustrates that Tracks Energy is actually performing well against industry competitors. This performance does not indicate, on an absolute value basis, that Tracks Energy does not have a lot of capital tied up in obsolete inventory; only that obsolete inventory is a relatively small percentage of total inventory. This metric can be misleading for companies that carry excessive amounts of material that is considered active.

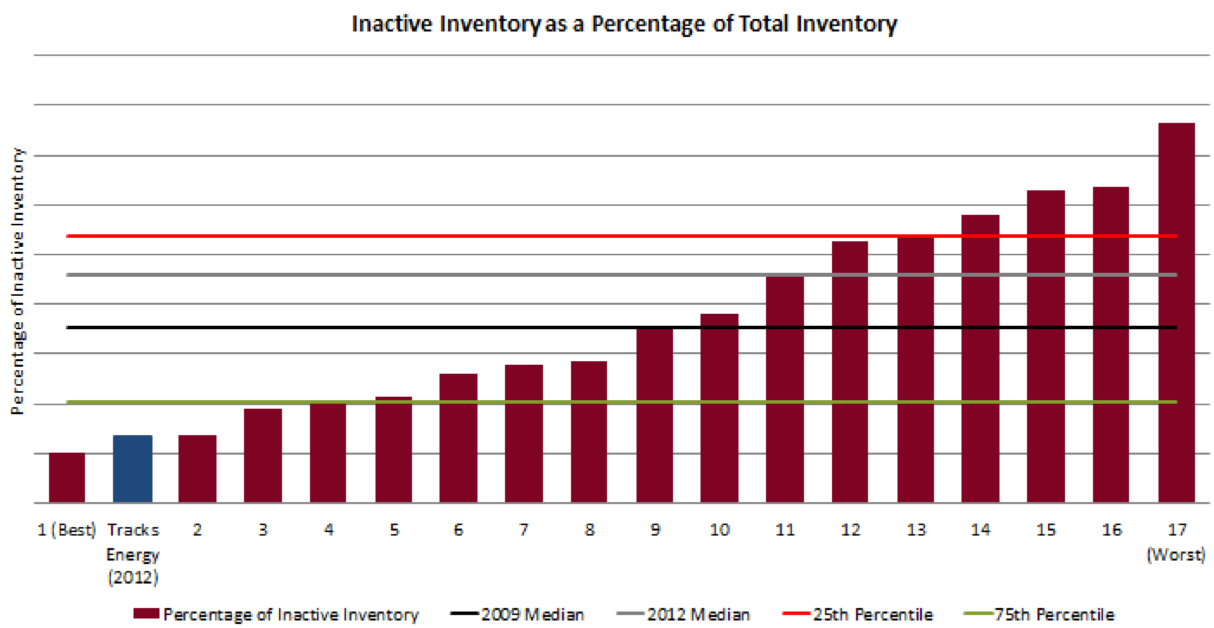


Figure 12 – Inactive Inventory Percentage

4.5.5 Inventory Value per Customer

For benchmarking purposes, we decided to get a baseline for inventory value per customer. Performance for this metric can be influenced by a variety of factors (e.g. service area, population density, customer demographics, network complexity, etc.); however this is a metric that can be used by regulators as a sign of inventory efficiency.

$$Inventory\ Value\ per\ Customer = \frac{Total\ Inventory\ Value}{Total\ Number\ of\ Customers}$$

Equation 5 – Inventory Value per Customer

Tracks Energy's performance in this category is slightly above average for this metric. Their network is relatively complex given the size of their service area, and age of legacy utility systems. An improvement in supply chain efficiency should lead to lower inventory values, which will improve performance in this category. Figure 13 below shows a comparison for inventory value per customer between Tracks Energy and other utility providers.

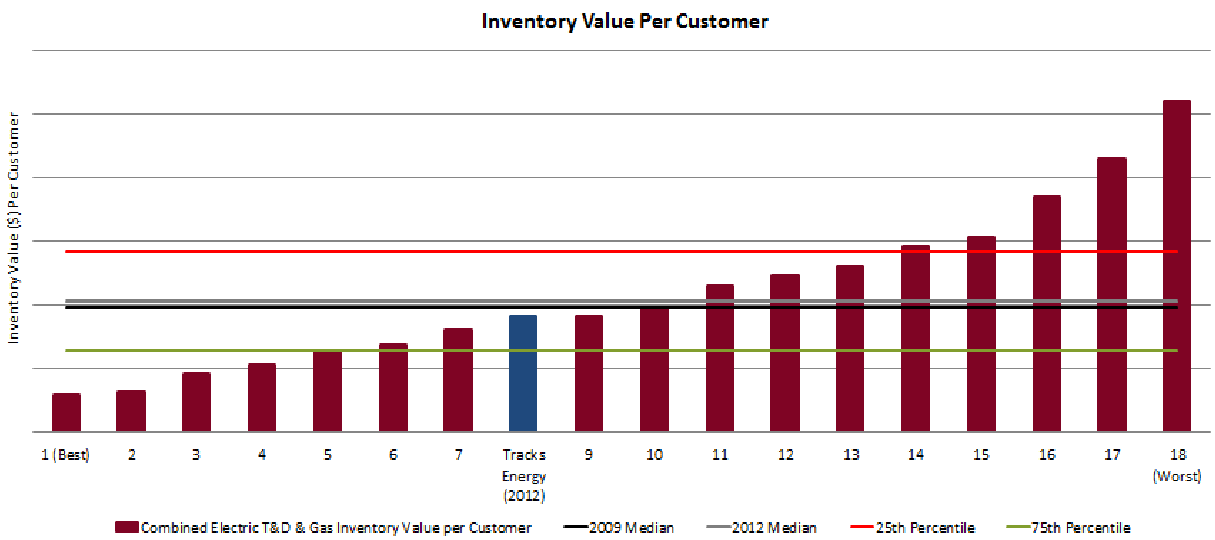


Figure 13 – Inventory Value per Customer

4.5.6 On Time Purchase Order Receipts

The other metrics we have presented so far help to summarize supply chain performance, but we now turn to analyzing on time purchase order (PO) receipt as an important aspect of planned work material fulfillment. Since the project start date is known, and expected lead times are known, the ability to receive POs on time is critical to receive project/program materials and fulfill them to work sites without causing delays. The ability to order planned work materials just in time can reduce the amount of capital required to carry these materials in inventory. We used a trailing 9 month sample of data with Equation 6 to calculate the performance of this metric.

$$On\ Time\ Purchase\ Order\ Receipts = \frac{Total\ number\ of\ POs\ received\ on\ time}{Total\ number\ of\ POs\ created}$$

Equation 6 – On Time Purchase Orders

Figure 14 below shows that improving on time PO receipts may be an option to improve supply chain efficiency. Based on the interviews we conducted, we learned that engineers ordering materials often padded their requested dates by 45 days in order to increase the likelihood that their materials would be in stock by the time a project/program began. In order to reduce planned material inventory expenses, we will need to improve this metric. We believe this is a realistic expectation since other utilities use the same suppliers that Tracks Energy does.

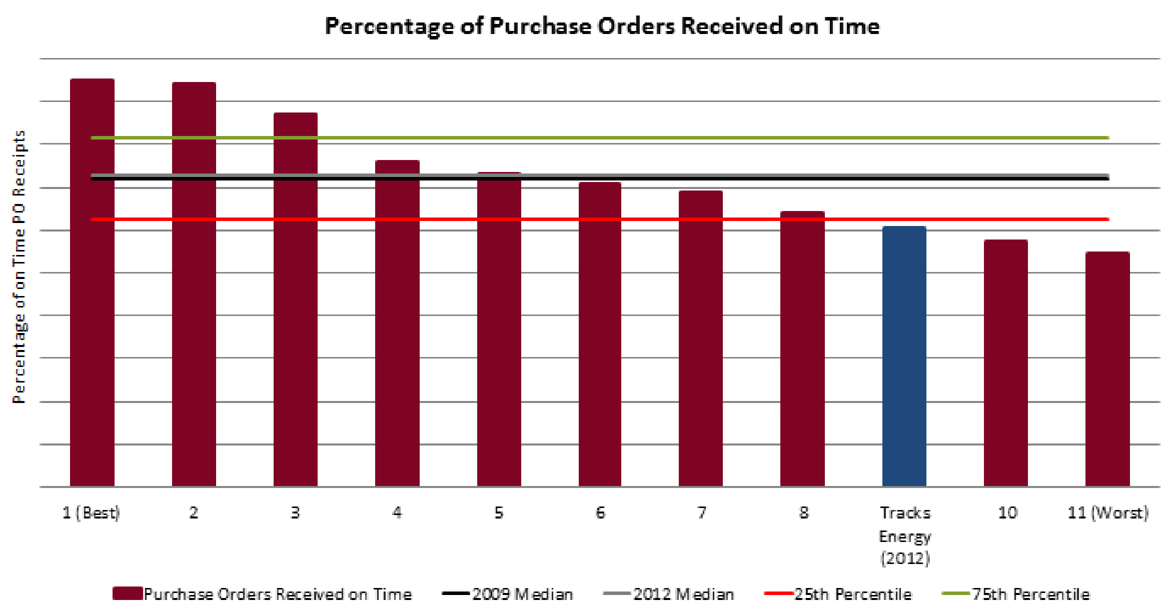


Figure 14 – On time Purchase Order Receipt Percentage

4.6 Chapter Summary

In this chapter we presented a summary of our process map development which yielded insight into the way the supply chain currently operated. We confirmed the process and information gaps identified through the process map development by benchmarking Tracks Energy against other utility industries. We utilize the framework provide by Lee & Billington (1992) in order to summarize our findings of the current state. Figure 15 below provides a summary of observations based on the applicable pitfalls of supply chain management. In the following section we will outline process improvement initiatives that will collectively become the supply chain process roadmap for Tracks Energy.

Pitfalls	Symptoms
No supply chain metrics	Supply chain metrics are not currently updated or reviewed. Performance measures were abandoned due to the belief they were incomplete.
Inadequate definition of customer service	CDC fill rates are not used to define customer service, and thus response times and backorder profiles are not tracked. All customer service information is related to
Inaccurate delivery status data	Material delivery information is tracked by internal software that triggered the transshipment of units from CDCs to crew barns.
Inefficient information systems	Information systems used by the various operational groups are disconnected, and not manually synced regularly. Each engineering discipline uses their own CAD
Ignoring the impact of uncertainties	Project and program delays are not tracked, or investigated for root cause analysis. Lead times, economic order quantities, and reorder points are static. Supply chain uncertainties are excluded from inventory policies.
Simplistic inventory stocking policies	Inventory policies do not differentiate between random and planned demand. The policies are manually updated based on heuristics developed by material planners.
Poor coordination	The actions of the project planning groups are disconnected from the operational decisions made by procurement, investment planning, and construction.
Incomplete shipment methods analysis	Procurement of materials is based on purchase price, and ignores the impact of lead times on inventory cost.
Incorrect assessment of inventory costs	Inventory holding costs are considered to be identical to the cost of capital for Tracks Energy as a whole. The cost of holding obsolete inventory, and the need for leasing 3rd party warehouse space is not considered.
Organizational barriers	Supply chain performance is not considered a key competency for Tracks Energy and is excluded from consideration by the majority of the operational groups. Functional silos reinforce independent actions and goals.
Separation of supply chain design from operational decisions	Decisions are made based on end customer impact independent of supply chain implications. SKU proliferation is common based on work crew requests, however the impact to the supply chain has only recently been considered.
Incomplete supply chain	The current focus is on internal supply chain operations, and once processes are defined, a more global perspective will be undertaken.

Figure 15 – Tracks Energy Current State Supply Chain Pitfalls

Chapter 5: A Strategic Roadmap to the Future State

With a comprehensive understanding of current operations and performance, we turned our attention to developing a strategic roadmap for improvements over the next three years. We used our lessons learned from the process map development, combined with our benchmarking analysis, to identify process improvement initiatives. For Tracks Energy to track their progress against these initiatives, it was important for us to develop a scorecard. Finally, in order to validate our process improvements would lead Tracks Energy in the right direction; we developed an outline of the future state performance.

5.1 Process Improvements

Based on our lessons learned from the process map development, observations we made at crew barn locations, and our data analysis, we developed a list of 15 strategic opportunities. We were also able to validate the necessity of 8 other strategic opportunities that were previously identified by the inventory management group as part of their own internal process improvement plans. In this section we will present the three opportunities that are the highest priority based on effort required and estimated benefit.

We uncovered many different issues from interviews with the various stakeholders and interviews at the CDCs and crew barns. We then walked through the process map to identify where the issues likely originated in order to propose a solution to the root cause of the issue. Once we were comfortable with the proposed solution, we determined the complexity of the proposed solution based on investment requirement, how drastic the change was from the current process, and how many departments were impacted by the change. The final step was to determine a realistic expectation for the impact of the proposed solution using the data available. The primary sources of data available were demand by CDC and requesting crew yard, POs placed from CDCs to suppliers, annual inventory snapshots, project and program work schedules, and unit fill rates for each request from each crew yard to each CDC.

We validated our complexity assumptions with the various stakeholders in order to verify our assumptions for each proposed solution. We also used historical data for inventory levels, and fulfillment performance in order to develop conservative estimates for the financial impact of our suggested changes. We compiled the complexity and financial benefit information into the complexity vs. benefit matrix depicted in Figure 16.

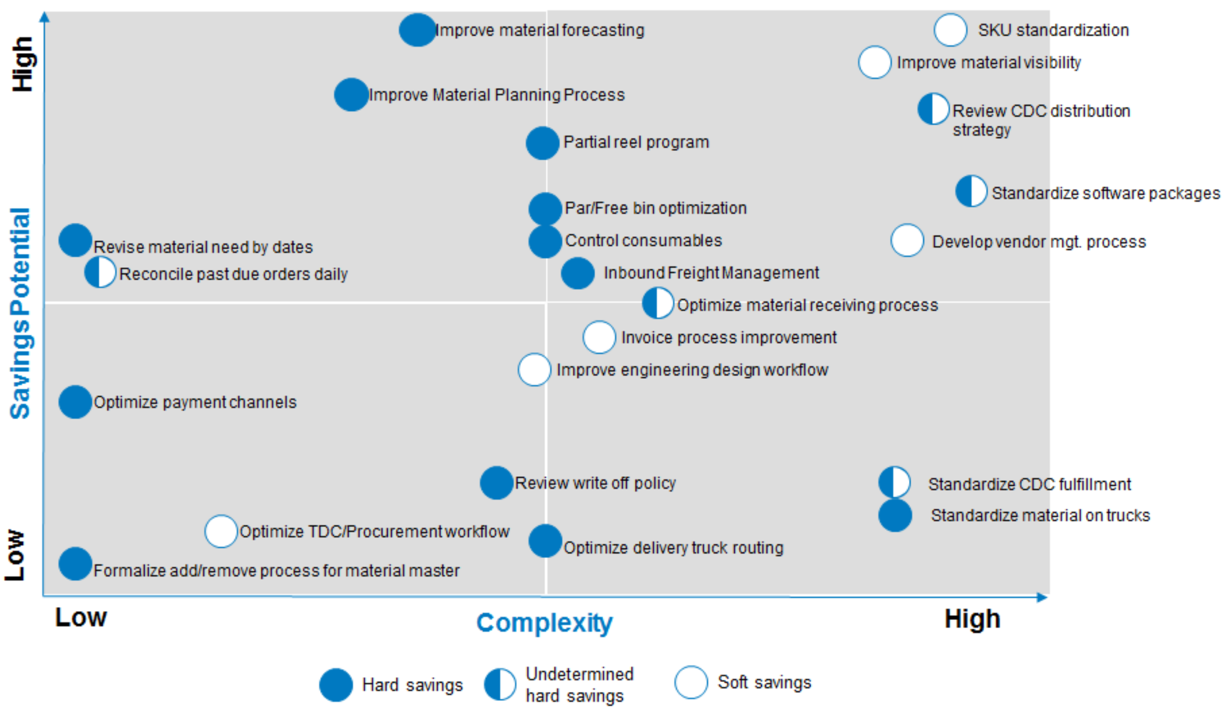


Figure 16 – Savings vs. Complexity Map of Process Improvements

For many of the proposed process changes, we were able to identify hard savings, actual dollar savings. For five of the initiatives, we were able to determine the opportunity to realize hard savings, however the data was not available to realistically quantify the value. The remaining six initiatives that we identified would lead to reduced workloads for individuals, but it was not realistic to assume they would lead to reductions in the workforce. We refer to these opportunities as soft savings.

The opportunities in the top left quadrant represent the highest priority issues since they yielded the most improvement with the least amount of effort. The opportunities in the bottom right quadrant have the lowest priority since they are very complex, and do not yield significant savings compared to the other opportunities.

5.1.1 Improve Material Forecasting

One of the issues that engineers, resource managers, and work crews highlighted was the delay in getting material to the work crews in spite of the BOMs that were developed during the engineering phase. We were able to validate these observations as legitimate issues based on the observed fill rates we analyzed.

The process map exercise, combined with our analysis of project and program schedule changes, revealed the material need by dates entered into the inventory management database were commonly incorrect for two reasons.

1. **Incorrect dates in the inventory management system**: Dates entered by engineers were based on original sanctioning documents that secured the funds for projects and programs. Roughly 40% of the projects and programs did not begin within 7 days of the original estimate. The schedules were adjusted at monthly construction meetings, however the changes were not communicated to inventory management or procurement.
2. **The inventory management system does not allocate material by project**: The inventory management software does not allow planners to designate material by planned material requests. The fulfillment of materials is on a first come first serve basis, so even when the material is procured in time, another project or program had the ability to "steal" the inventory.

Material planners have experienced both ordering material too early, and too late based on the need by dates they see in the system. When planners ordered material too early, excessive stock would remain in the CDC (sometimes up to a year when projects/programs were delayed significantly) which caused space and safety issues for the CDC workforce. If planned work was pulled ahead of schedule, the material planners were forced to scramble to find material to fulfill the material request. The current practice of material planners is to use their own best judgment based on past experiences and product lead times to determine when they should order material.

The solution to this problem is to revamp the material planning process. As we discussed earlier, procurement and inventory management are not involved in the annual planning process, and thus have little visibility to projected demand in the coming year. The inability to understand what to expect leaves these two departments blind as potential problems begin to develop. The result is routine firefighting of issues when stock outs occur. The integration of all supply chain stakeholders into a single annual planning process is critical. Also, the inclusion of material planners and procurement personnel at monthly construction meetings will serve as a check to validate stock levels are adequate. Attendance for the inventory management team is necessary to update need by dates in the inventory management software.

To calculate the savings for this opportunity we first calculated the average number of days planned project and program work were delayed in 2012. We determined that current processes were not consistent enough to plan for just in time delivery and receipt of project and program materials. In order to account for process inconsistency and to protect planned work from delays, we added a buffer of 15 days of planned work holding costs. A buffer of 15 days was selected based on the historical on time purchase order receipts, and to allow a two week buffer for projects to be pulled ahead. We then calculated the holding costs associated with holding project material for the average number of days work was delayed. The formulation for calculating the savings for this initiative is outlined below:

$$Average\ Schedule\ Change(ASC) = \frac{\sum_i^n (Project\ Actual\ Start\ Date_i - Est.Project\ Start\ Date_i)}{Total\ number\ of\ projects}$$

Equation 7 – Average Planned Work Delay (in Days)

$$Project\ Material\ Expense(PME) = (\%\ of\ Material\ Spend\ for\ Planned\ Work) * (Total\ Material\ Spend)$$

Equation 8 – Project Material Expense

$$Planned\ Work\ Holding\ Costs\ =\ (ASC - 15\ days) * (PME) * (Daily\ Material\ Holding\ Costs)$$

Equation 9 – Planned Work Holding Costs

The complexity of this opportunity is relatively small since all of the information is available through existing processes, and it only requires the additional alignment of procurement and inventory management. The projected savings was determined to be 12% of annual inventory holding costs based on comparing the calculated planned work holding cost to the actual projected holding cost of planned work material. Data was not available for costs associated with planned work delays, so those savings were excluded from our analysis.

5.1.2 Improved Material Planning Process

During our interviews with the inventory management team members, we learned that the inventory management systems did not contain dynamic data for ordering guidelines. Reorder points, lead times, and economic order quantities all have significant influence over inventory cost and supply chain responsiveness. Our inventory analysis showed that demand was inconsistent year over year for many of the active inventory SKUs.

The solution to rectify deficient inventory policies was to develop an annual review process to be conducted by the inventory management team. This process would incorporate annual planning information along with usage information from the previous year to update inventory policies for the top 6% of SKUs by throughput (SKU cost x annual demand). Tracks Energy will have SAP enabled in 2013 to provide guidance for updating reorder points, lead times, economic order quantities, and safety stock levels based on observed demand. Updating SAP calculations with current year projections will improve the cost and responsiveness of inventory policies.

The complexity of this opportunity is relatively high given this new process will be technical in nature, and it isn’t clear the skills required are internally available. This opportunity is still a high priority considering the implications of having inefficient supply chain policies that are also unresponsive. We developed a savings estimate of 27% of total inventory value based on the development of our own inventory policies which will be covered in more detail with the inventory modeling in Chapter 6.

5.1.3 SKU Standardization

Our analysis surrounding SKU demand revealed that 43% of the active SKUs, excluding critical spares, had no demand in over the previous two years. In addition, the only requirement to add a new SKU to inventory was to fill out a request form. The apparent result of this policy is multiple SKUs that were directly substitutable. Examples of this SKU proliferation could be seen across materials such as tools, gloves, safety glasses, and ladders. Our analysis showed that only 12% of all SKUs were common across all five of the CDCs. Data available was not detailed enough to see how far into capital materials this proliferation existed, and thus a hard savings was not able to be reasonably estimated.

We determined this opportunity was a high priority, in spite of being in the top right quadrant, because of the cost implication of carrying redundant inventory, and the responsiveness implications of not being able to share materials between regions during emergency responses. In addition, reducing the number of different SKUs stocked will simplify material planning, procurement and ordering. The high complexity rating for this initiative was based on the impact changes would have to the unionized workers, who have a history of requesting a variety of similar materials to be available based on individual preferences.

5.1.4 Section Summary

In this section we presented our opportunity complexity vs. benefit map as a useful framework for prioritizing a large group of opportunities. We included the details of the three highest priority opportunities to highlight the effectiveness of using process maps and data analysis to develop our strategic roadmap. In the next section we will turn our focus to performance tracking through the use of a simple, yet comprehensive, scorecard.

5.2 Scorecard Development

The development of a supply chain scorecard was not only important for understanding the baseline performance presented in Chapter 4, but also for tracking progress to plan and engaging stakeholders. The primary objective for the scorecard development was to select a limited number of key measurements that were easy to obtain, and measured critical aspects of internal supply chain operations. The SCOR model we quickly excluded from consideration due to the elaborate needs for data tracking, and the overwhelming number of measurements provided. Since Tracks Energy was not tracking any system wide supply chain information consistently, we decided to start with the basics.

The basis for selecting which metrics to populate the scorecard were adapted from the frameworks of Lapide (2006), and Doran (1981) reviewed previously in Chapter 2. Each metric we selected was designed to meet the following qualifications:

1. Supports existing U.S. Priorities and Global Strategy
2. Aligns with the operating responsibilities of a specific stakeholder
3. Directly actionable by specific stakeholder to positively influence metric performance
4. Executes well against a balanced set of competitive operational performance objectives
5. Reinforces other metrics to support the operating model
6. Available through SAP reporting system to ensure timely availability
7. Conflicting incentives between metrics were understood

In order to verify our selected metrics abided by our framework we completed the form shown in Figure 17 below for all metrics.

Metric name	CDC Order Fill Rate
Metric description	This metric will report the par/free bin fill rate, inventory fill rate, and capital request fill rate a percentage of total orders (complete orders filled)/(total orders requested)
How does the metric support U.S. Priorities / Global Strategy	This metric supports customer satisfaction by providing material on time when it is requested. The CDC fill rate will impact the End User Fill Rate which directly impacts
What key process does the metric measure	This metric will measure the ability of the CDC to fulfill orders in the right quantity at the right time to work sites and crew barns. This metric measures the ability of the supply chain to supply all materials necessary to completely satisfy customer orders.
How often is the metric data compiled	Weekly
How often are countermeasures reviewed	Monthly
Source/Location of Data	Data is available through PeopleSoft as part of the Service_Level_Agreement_SLA weekly query output file. Oracle data is not available for this metric. SAP object ID 1788 (Order Fill - Line fill Rate Report) will be available after the launch of SAP.
Owner of Metric Calculation	Inventory Management
Who owns action items	Inventory Management
Why is this department the correct owner	The Inventory Management team owns the CDC operations, material reorder points, and the material operations at crew barns. The CDC order fill rate is under the direct influence of Inventory Management.
What action is taken if the metric indicates a problem	The inventory management team will need to investigate the root causes of misses and implement corrective actions to improve performance.
What negative impact might this metric cause	Fill rates are directly related to inventory holding policies. The incentive will be to hold more material to ensure fulfillment. It is important that this metric is balanced with cycle stock inventory turns to maintain the minimum amount of inventory required to achieve desired
Additional Info	Fill rates for Par/Free bins, inventory, and Capital work can't be tracked separately without additional queries to tie accounting information back to the MSR/S-Order. A long term goal should be to measure emergency/storms performance separate from project/program performance.

Figure 17 – Metric Development Form

Before populating the scorecard in Figure 18, we used the guidelines Yves (2003) provided as a sense check to ensure we had created a tool that was useful. The scorecard also utilizes a trend tracking formulation to clearly identify data trends. The "Dash Board" section is intended to indicate performance to goals and month over month trends. Red arrows indicate the current performance is below the target, and green arrows indicate performance is above the target. If the arrow is pointing down, it indicates degradation in performance over the last month. If the arrow is pointing up it indicates that current performance is more favorable to the goal over last month. Horizontal arrows indicate performance has been flat month over month.

Inventory Management FY2012 - Scorecard Layout 2012						
Measure	Performance Previous FY	Comments	Performance	Previous Month	Dash Board	2015 Goal
Project/Program Performance to Plan	N/A	Reported as FY Projects/FY Cancelled/FY Delayed/FY Ahead of Schedule (Preliminary Engineering - Construction)	619 / 1 / 231 / 101	N/A	↓	N/A
CDC Par/Free Order Fill Rate	N/A	Reported as the percentage of STORMS and MSR Orders that are filled completely	77.3%	N/A	↑	95.0%
CDC Par/Free Line Fill Rate	N/A	Reported as the percentage of total units filled for all MSR and STORMS orders	87.3%	N/A	↑	98.0%
Inactive Material	N/A	Reported as the inventory value of material that has no activity since 2010	13.85%	N/A	↔	1%
Net Discounts Claimed	N/A	Percentage of invoices successfully processed with discounts against all invoices processed with discounts available.	85%	N/A	↑	90%
Cycle Stock Inventory Turns	N/A	Reported as the inventory turns for all inventory materials excluding emergency stock	1.65	N/A	↓	2.35
Total Stock Inventory Turns	N/A	Reported as the inventory turns for all inventoy material including emergency stock	1.37	N/A	↑	1.82
On Time PO Receipts	N/A	Reported as the percentage of POs arriving on or prior to the due date for FY2012	60.7%	N/A	↑	81%
On Time POs with 7 day grace period	N/A	Reported as the percentage of POs arriving less than 7 days after due date for FY 2012	77.0%	N/A	↔	85%
Total Inventory Value	N/A	Total value of inventory including emergency stock	$ 121,561,894	N/A	↔	$ 91,659,894

Figure 18 – Proposed Tracks Energy Supply Chain Scorecard

The development of a scorecard that accurately measures performance is critical to help motivate employees, and provide a basis for rewarding the desired behaviors (Behn, 2003). Now that we have outlined the current supply chain performance, and created a scorecard for tracking improvement, we turn to projecting the impact of our strategic supply chain roadmap.

5.3 Projected Performance

The final step in outlining the strategic supply chain roadmap is to identify the future state performance based on resolving the opportunities presented in Section 5.1. This exercise is not only important for setting expectations, but also for solidifying commitment from stakeholders to achieve the performance improvements they helped to outline.

In this section we will present performance projections based on the benchmarking information presented in Chapter 4. The calculations we used for these metrics are identical to those presented in Chapter 4. Showing the detailed calculations for financial and performance improvements would expose proprietary information, so we do not present the explicit calculations here. The expected improvements are presented here to highlight the importance of understanding where this specific supply chain improvement roadmap will take Tracks Energy.

5.3.1 CDC Order Fill Rate

The CDC Order fill rate is expected to dramatically improve based on the following initiatives:

1. Improve Material Forecasting
2. Improve Material Planning Process
3. SKU Standardization
4. Revise Material Need by Dates
5. Reconcile Past Due Orders Daily
6. Improve Engineering Design Workflow
7. Standardize CDC Fulfillment

The combination of these initiatives are expected to improve the CDC order fill rate by increasing visibility to planned demand, simplify order fulfillment, and highlighting potential issues prior to construction start dates. The combined effect of these initiatives is illustrated in Figure 19 below.

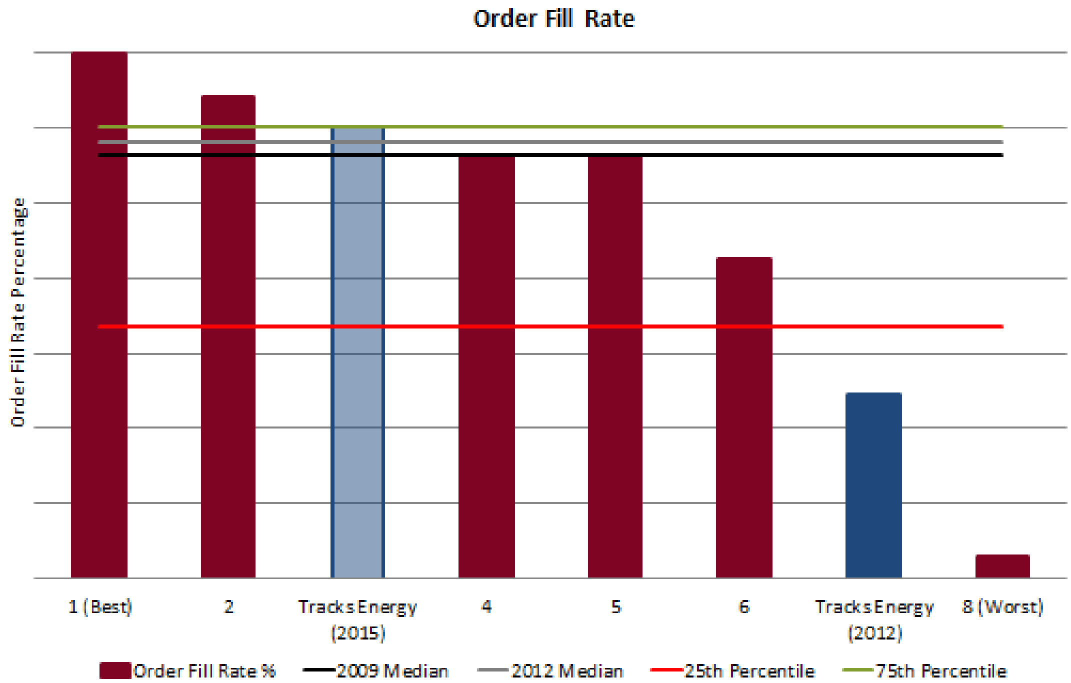


Figure 19 – Order Fill Rate with Projected 2015 Performance

Improving the order fill rate will be essential to restore confidence in the inventory management process, which will lead to lower holding costs as planned work materials are able to be delivered just in time. The utilities involved in this benchmarking study have shown a marginal increase from 2009 to 2012 based on the median performance, however we believe Tracks Energy will be able to move into the top 25th percentile by 2015.

5.3.2 CDC Line Fill Rate

The CDC line fill rate is positively influenced by the same initiatives presented in Section 5.3.1. The successful execution of a SKU standardization process will have a significant effect on the expected line fill rate by decreasing the number of SKUs currently stocked in inventory, reducing the potential stock out of items that currently have direct substitutes.

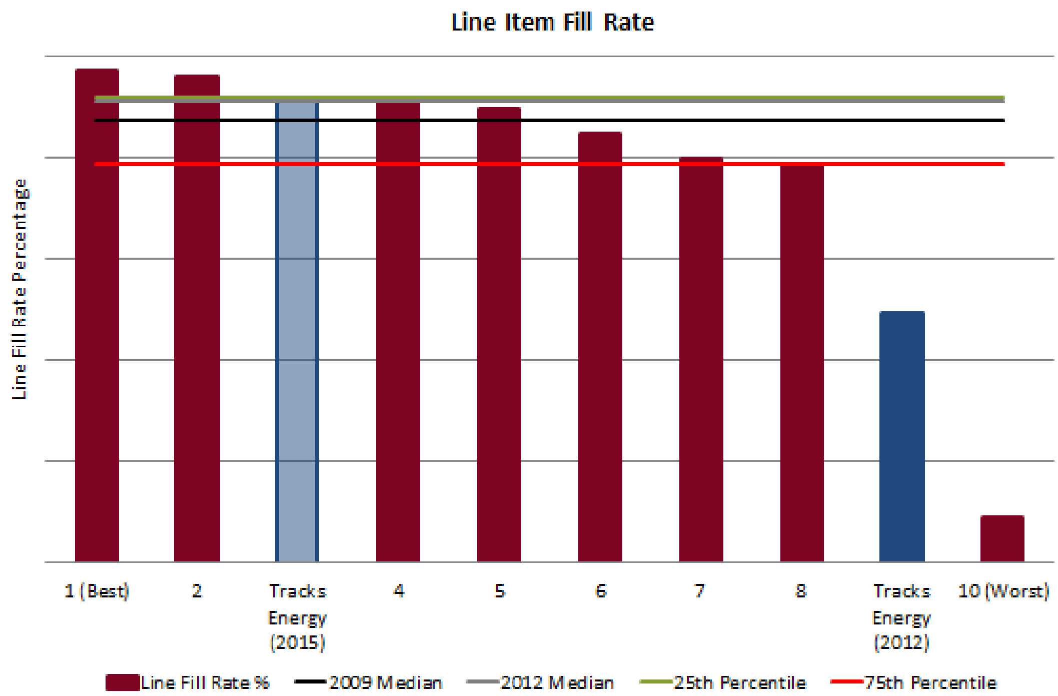


Figure 20 – Line Fill Rate with Projected 2015 Performance

Figure 20 above shows that we expect a dramatic improvement by 2015 based on the implementation of several key initiatives. The utilities in this study show a similar improvement for their line fill rate as they did for their order fill rates from 2009 to 2012. Based on our analysis and conservative expectations, we expect to see Tracks Energy performing in the top 25th percentile of the utility industry.

5.3.3 Inactive Material

Tracks Energy was already performing well against their peer group for inactive inventory as a percentage of total inventory. Successfully executing the SKU standardization project, reviewing the write off policy, and formalizing the add/removal process for materials will provide the foundation for Tracks Energy to set the industry standard for this metric.

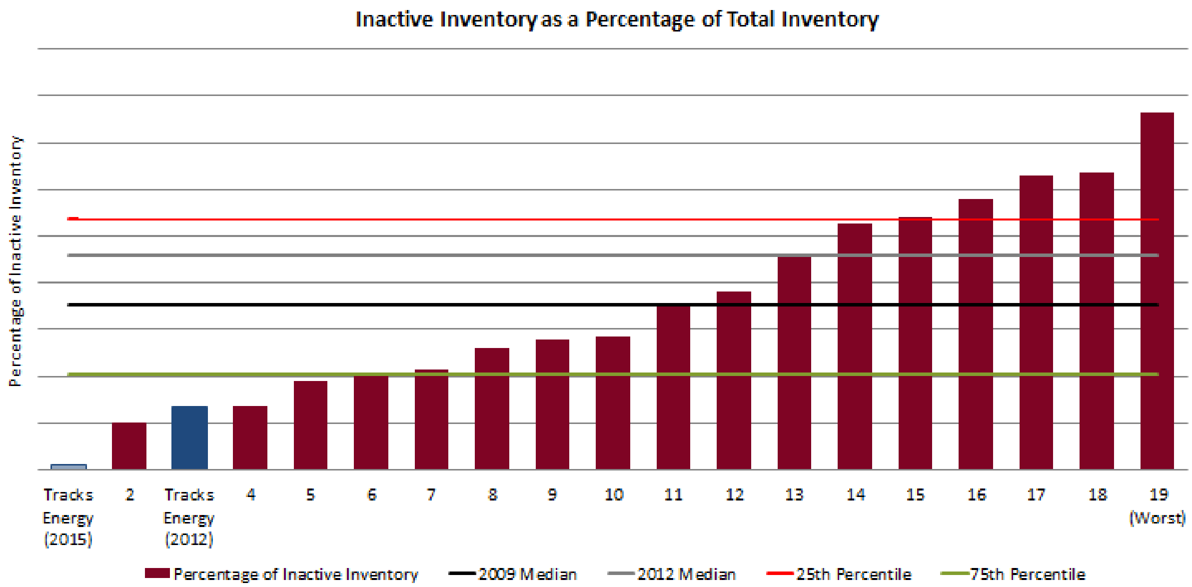


Figure 21 – Inactive Inventory Percentage with Projected Performance

Figure 21 above highlights our optimistic expectation for improvement based on effectively removing obsolete materials from inventory, excluding critical spares.

5.3.4 Total Stock Inventory Turns

Inventory turnover performance is expected to improve based on the timely procurement of planned work materials, in addition to inventory reduction opportunities. The complexity of the gas and electric networks, in addition to critical spare regulations, require a long tail of low demand items to be stocked in inventory.

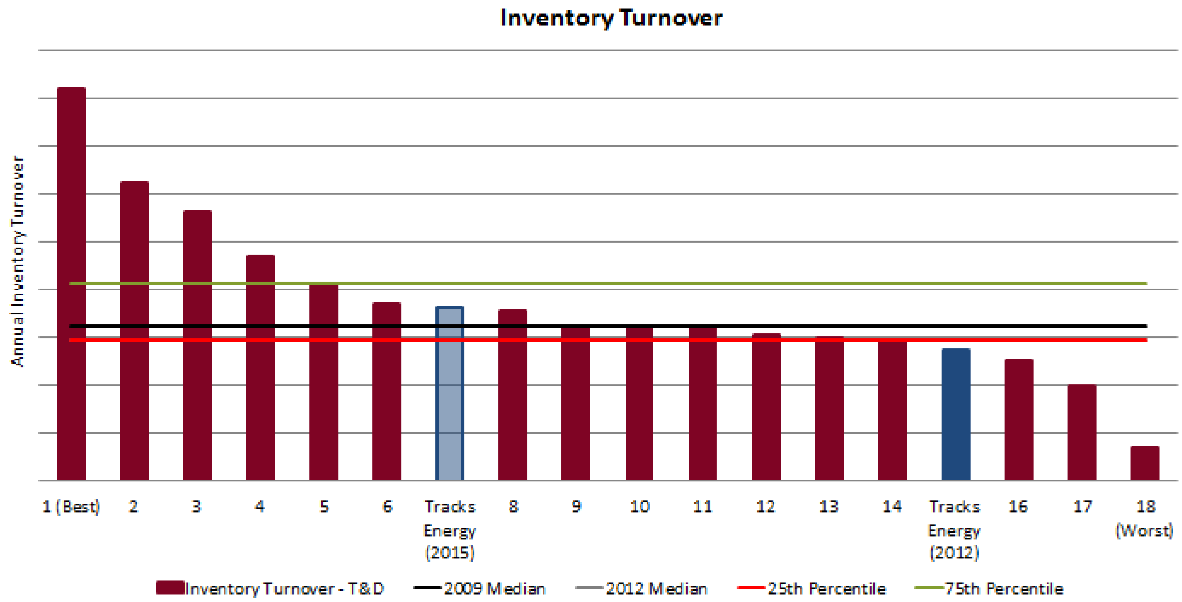


Figure 22 – Inventory Turnover with Projected Performance

Figure 22 shows a less dramatic improvement than many of the other initiatives, which is partially related to our inability to estimate the true impact of SKU rationalization. This metric is also difficult to compare apples to apples with other utilities due to varying ages of networks included in the benchmarking study.

5.3.5 On Time PO Receipts

The anticipated improvement of on time PO receipts is directly related to reconciling past due order daily. During our interviews with inventory management personnel we learned that past due POs are not proactively resolved until a stock out occurs. An analysis of the past due order report showed that items up to a year and a half past due were unresolved. A major stock out event occurred at the end of the construction season which resulted in a negative impact to work crews. All of the open items on the past due order report were researched, which uncovered a software ordering issue that prevented 33% of the delinquent orders from ever being received by vendors. The SKU standardization initiative will also help to reduce the volume of delinquent orders by reducing the number of active SKUs for the network.

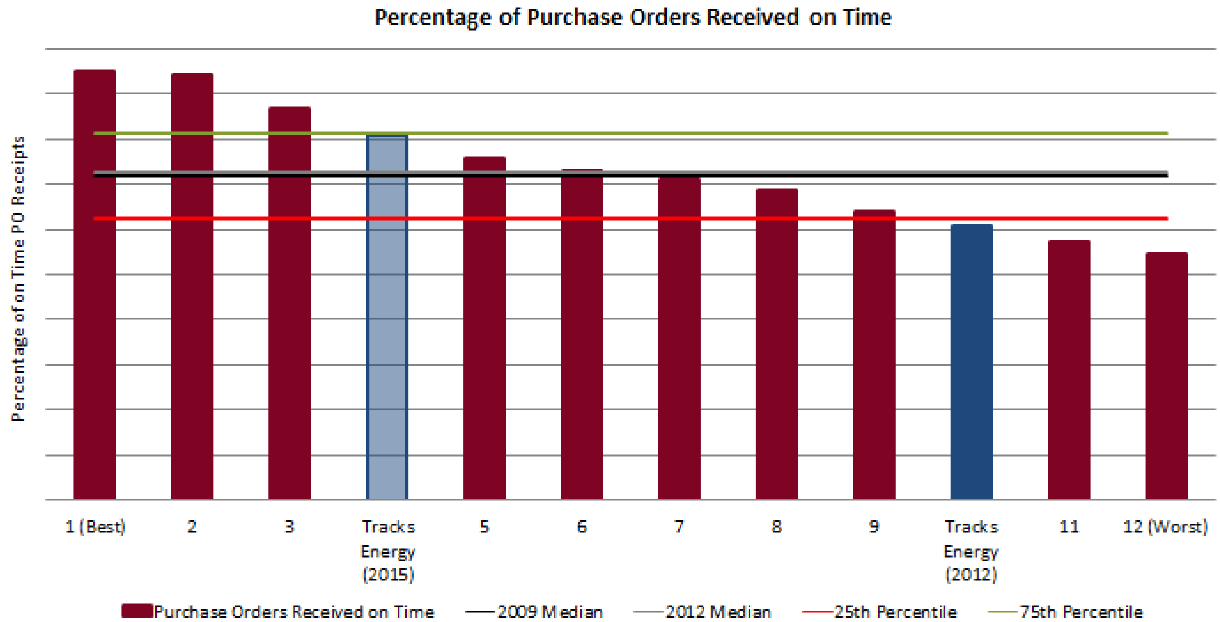


Figure 23 – Percentage of Purchase Orders Received on Time with Projected Performance

Figure 23 above shows the projected improvement for on time PO receipts by 2015. Improving the material planning process will ensure the lead times are accurate, which will improve performance by excluding materials which are inaccurately reported as late. Improved performance for this metric will help to reduce variability in the material fulfillment process, which will decrease the amount of safety stock currently required to maintain responsiveness.

5.3.6 Total Inventory Value per Customer

Inventory value per customer is expected to moderately improve, however the large customer base of Tracks Energy anchors this performance improvement. By adjusting inventory values based on the expected influences of all of the initiatives presented in Section 5.1, performance is expected to improve to the 25th percentile (see Figure 24).

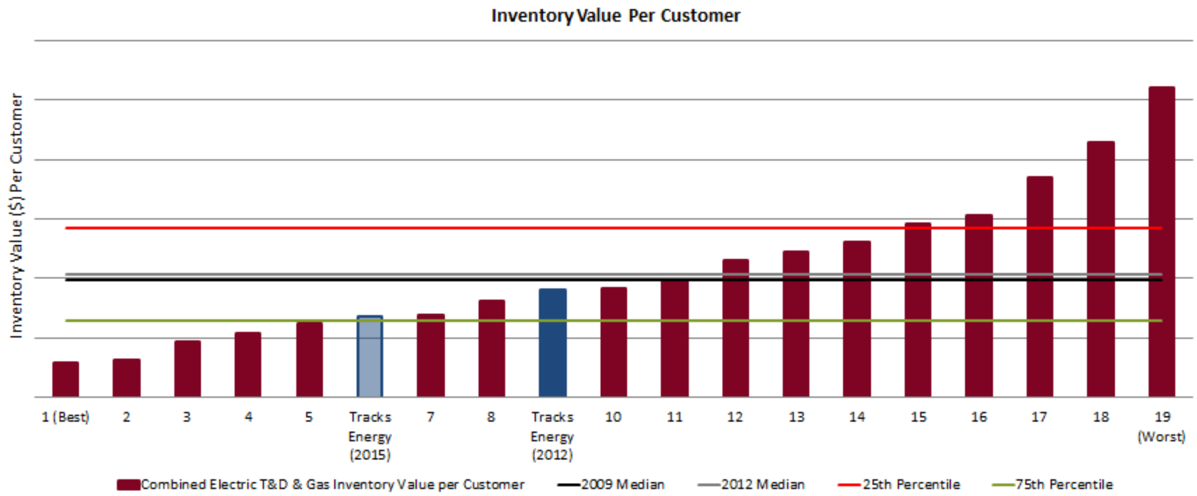


Figure 24- Inventory Value per Customer with Projected Performance

Projecting future supply chain performance based on a strategic vision is not an exact science. Since the utility market is relatively stable year over year, we believe that our conservative estimates based on data analysis are realistically obtainable. We believe it is important to set realistic expectations for improvement in order to create a foundation for continuous improvement. The framework presented so far is intended to be an iterative exercise in order to adapt supply chain strategy to the current market demands.

5.4 Chapter Summary

In this section we provided details of our strategic roadmap to a future state for the Tracks Energy supply chain. We demonstrated the usefulness of applying data analysis combined with process maps to identify process improvements directed at solving the root causes of negative observations. Data analysis was used to project the impact of our strategic roadmap, which was then benchmarked against other utilities to verify expected performance was reasonable. In Figure 25 below we provide a high level summary of how the initiatives presented as our strategic supply chain roadmap address the common supply chain pitfalls demonstrated by Tracks Energy.

Pitfalls	Symptoms
No supply chain metrics	To resolve this pitfall we proposed a monthly scorecard with ten key metrics that are easily accessible through the SAP reporting system
Inadequate definition of customer service	In order to increase awareness of internal customer service we have proposed tracking fill rates out of CDCs
Inaccurate delivery status data	Material delivery information is tracked by internal software that triggered the transshipment of units from CDCs to crew barns.
Inefficient information systems	To resolve the inefficiencies between information systems, we proposed consolidating the available software packages to standardize their use, and create automated connections to ensure all data is consistent between systems
Ignoring the impact of uncertainties	We proposed tracking project/program delays in order to begin understanding what drives variability in the schedules
Simplistic inventory stocking policies	We propose two alternate inventory modeling tools, which result in substantial capital investment, in order to highlight the need to develop optimal inventory stocking models. The implementation of SAP will also assist to resolve this pitfall
Poor coordination	We suggested a variety of linking mechanisms and policies to coordinate planning activities with operational tasks
Incomplete shipment methods analysis	We developed a strategic tool to provide additional analysis to understand the effects of purchase price and lead times
Incorrect assessment of inventory costs	Our strategic supply chain process improvement roadmap does not specifically address this pitfall, but it is expected to be addressed as supply chain management proficiency increases
Organizational barriers	The strategic roadmap includes a variety of linking mechanisms and policies to coordinate the goals of different supply chain stakeholders
Separation of supply chain design from operational decisions	The process improvements outlined in conjunction with scorecard performance goals will begin to align supply chain design with operational decisions
Incomplete supply chain	Our strategic supply chain process improvement roadmap does not specifically address this pitfall, but it is expected to be addressed as supply chain management proficiency increases

Figure 25 – Summary of Actions Designed to Address Common Supply Chain Pitfalls

Chapter 6: Inventory Model Design

6.1 Developing Inventory Policies based on a Simple Strategic Model

In this section we will present a strategic model we developed to highlight the cost of using simplistic inventory policies for inventory ordering. The development of this model was to (1) help understand the impact of existing oversimplified inventory policies, and (2) Illustrate the relationship between lead time and inventory costs. The model we present in this section will model random demand

and lead time as independent identically distributed (iid) normal random variables. Our model provides a strategic view of inventory stocking policies, and expected values for inventory investment and holding costs.

6.1.1 Model Development

Tracks Energy uses a modified A-B-C inventory classification scheme for each SKU. The classifications are fixed based on each item's throughput value (unit cost * annual demand). SKUs that represent 80% of the total annual throughput are classified as 'A' items. The next 10% of throughput is classified as 'B' items, and the final 10% of throughput is classified as 'C' items. All transformers are classified as 'X' regardless of throughput. Like many of the individual SKU characteristics, this classification has not updated on a regular basis. Figure 26 below summarizes the results of our data analysis of the A-B-C inventory classification scheme with the respective Tracks Energy classifications by percentage.

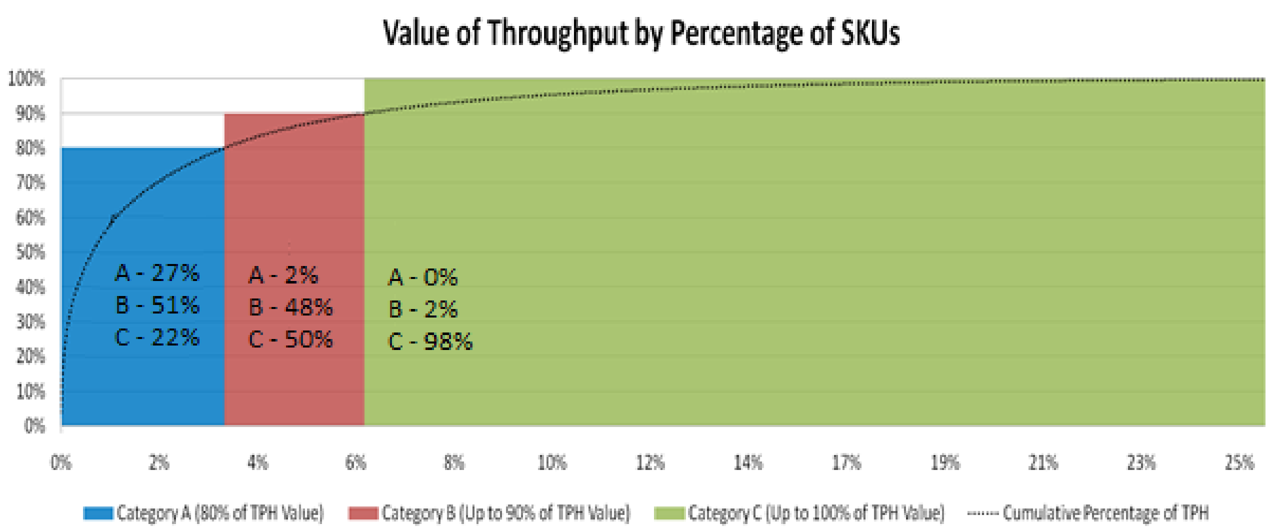


Figure 26 – Updated A-B-C Inventory Classification by Throughput Value

The A-B-C inventory classification scheme is a common approach for understanding which SKUs are the most important for an operation (Silver, Pyke, & Peterson, 1998). It is not cost effective, or reasonable, to treat all SKUs equally. For example, a bolt that is inexpensive and seldom used is not as important as a common distribution wire. The amount of time and effort needed to ensure the common wire is available is much higher than the inexpensive low use bold. The A-B-C inventory framework allows us to understand from a throughput perspective which SKUs likely require more attention than others.

Our analysis showed us that the existing classifications are outdated based on the observed 2012 demand. If inventory planners pay close attention to 'A' items, and not 'C' items, they could potentially be overlooking important SKUs from an inventory management perspective. For the remainder of this document, we will use our updated classification as follows:

1. A Items – Materials that account for up to 80% of the total inventory throughput value
2. B Items – Materials that account for 80%-90% of the total inventory throughput value
3. C Items – Materials that account for 90% -100% of the total inventory throughput value
4. D Items – Materials that had 0 units demanded in 2012
5. E Items – Materials that had 0 units demanded in 2011 and 2012

In order to develop the model for inventory policies, we wanted to ensure we were modeling decisions based on how the current supply chain operated. Figure 27 below shows the SKU stocking locations by as a percentage of total SKUs. For example, of the total active SKU catalog, 24% of the SKUs are unique to CDC1. Likewise, only 12% of the total active SKU catalog is shared between all of the CDCs. Figure 28 and Figure 29 illustrate the same type of analysis based on category A and category C items respectively.

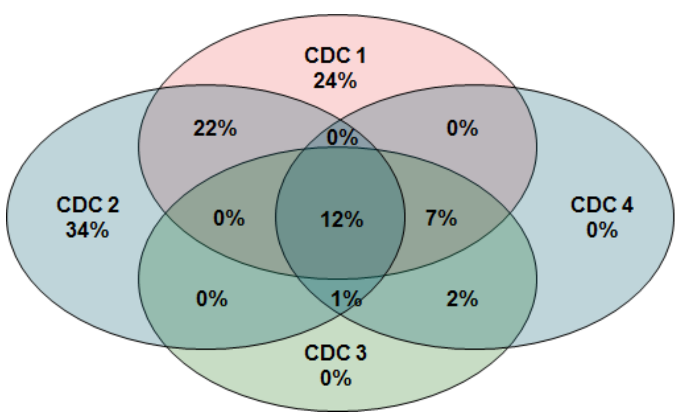


Figure 27 – SKU Stocking Locations for Each CDC by Percentage

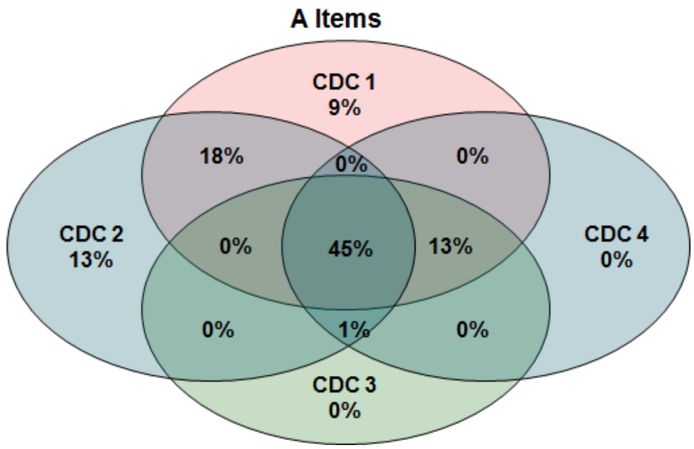


Figure 28 - SKU Stocking Locations by Percentage for A Items

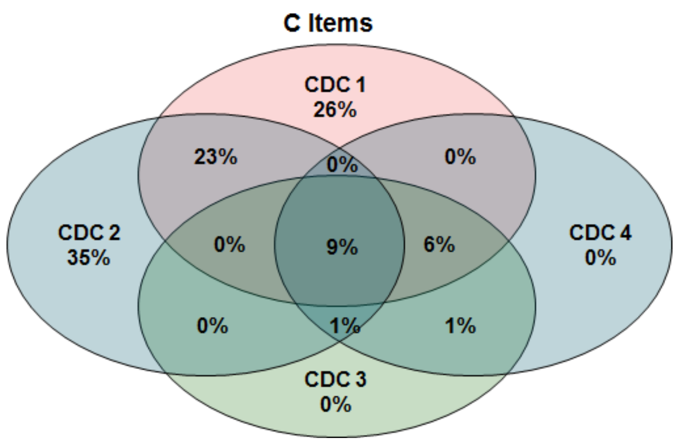


Figure 29 – SKU Stocking Locations by Percentage for C Items

The analysis presented in the figures above shows us that there is limited commonality between the items stocked at each of the four different CDCs. The figures also indicate that SKU standardization and rationalization between CDCs would increase the potential to transfer material between CDCs in the event a stock out occurs. Commonality of SKUs across the network would provide an opportunity for reducing inventory investment through the ability to pool risk across the entire network, instead of each CDC independently. Inventory transfers represent less than 3% of total inventory throughput. Inventory management stakeholders confirmed the lack of transfers, explaining that they only occurred as a last resort to satisfy random (emergency) demand. The lack of transfers and the lack of common SKU inventories by location led us to conclude that the inventory policy model should treat each CDC independently, without considering additional risk pooling by enabling transfers between CDCs.

Figure 30 below is a visual representation of the supply chain network.

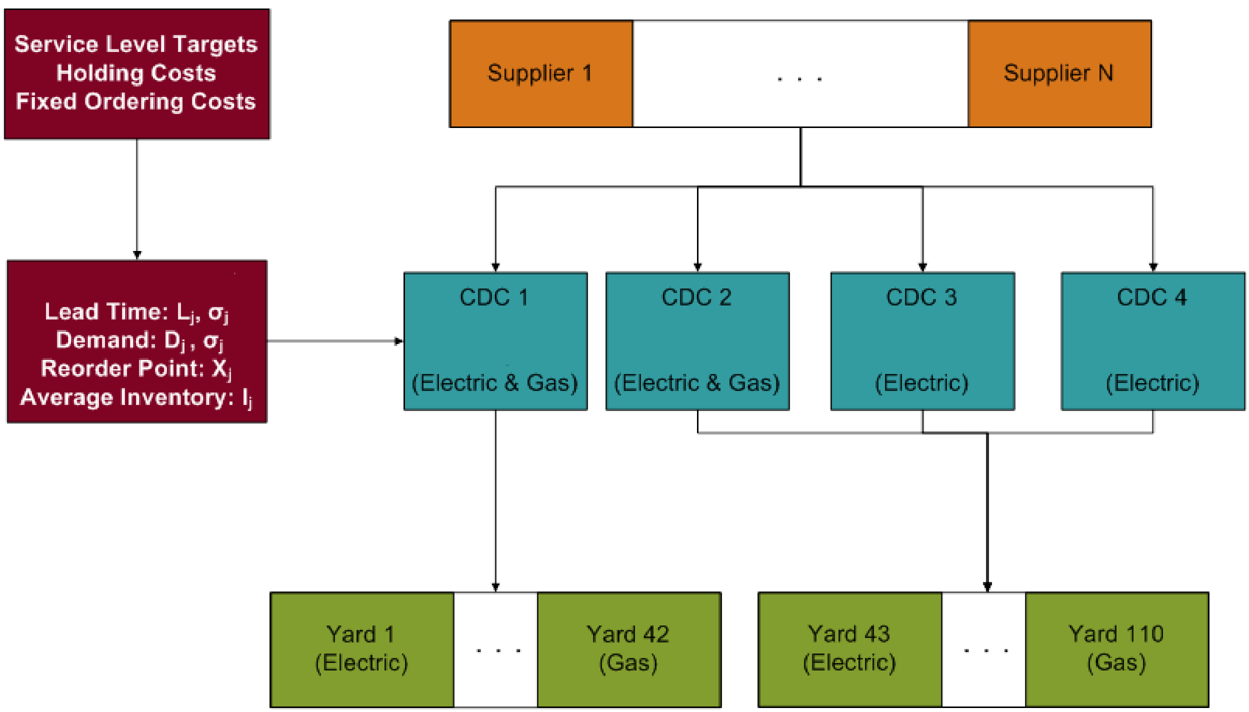
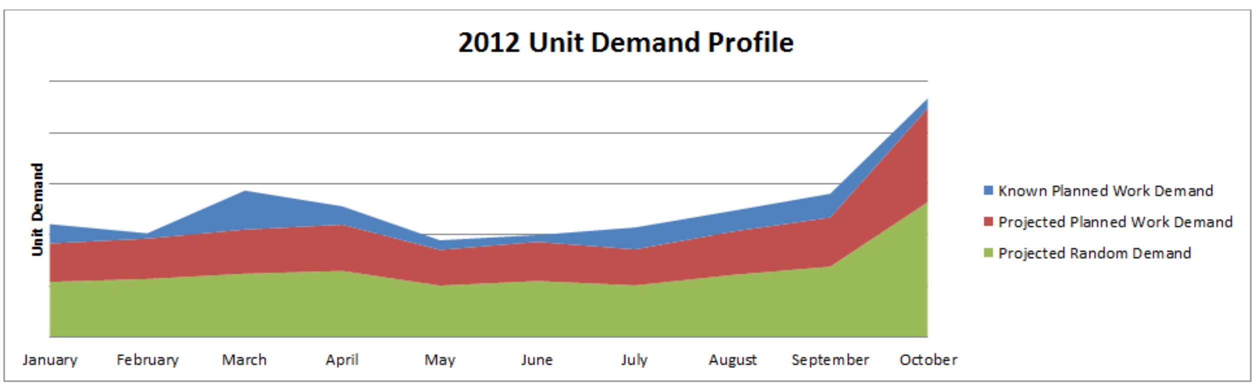


Figure 30 – Supply Chain Network for Strategic Inventory Policies

The service level targets for the model are designed to be set by inventory management. Holding and Fixed ordering costs are constants that should be updated annually based on the financial information available. Annual lead time and demand information should be calculated from procurement contracts and historically observed values to ensure the reorder points are calculated accurately by the model.

One other significant consideration was how to separate planned demand from random demand (see Section 4.1 for definitions). Unfortunately the inventory management systems did not allow us to completely distinguish random demand from planned project/program demand. Many of the supply chain stakeholders indicated that planned demand accounted for 50% of their annual budget, but we were never able to obtain supporting information from the finance team. Inventory policies are traditionally designed around minimizing cost based on random demand information. The lack of identification between planned and unplanned demand in our data forced us to make an assumption for random demand. We designed the model to let the user select the portion of total demand that was planned, which was then used to calculate random (unplanned) demand. An example of the resulting aggregate demand and value profiles are shown in Figure 31. For our strategic roadmap, inventory policies would be designed around the random demand portion of total demand, while planned demand inventory value would be based on the new processes outlined as part of the strategic roadmap in Chapter 5.



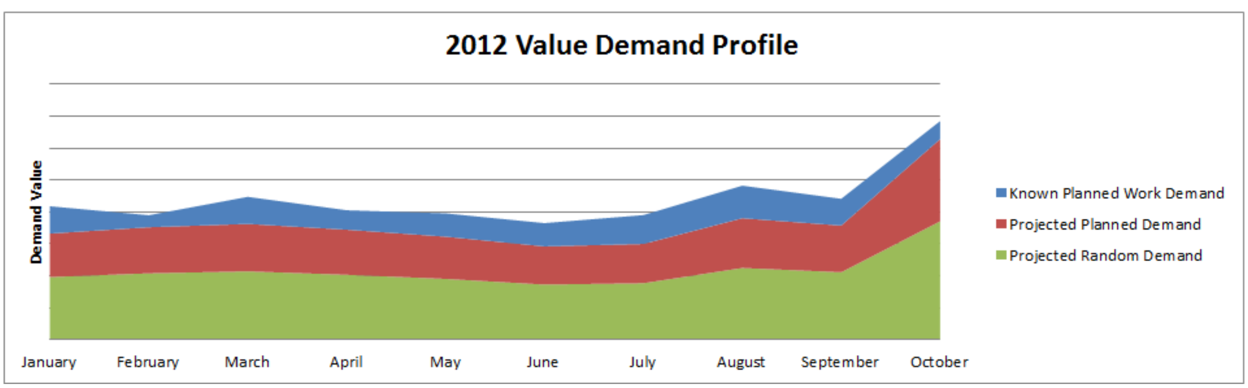


Figure 31 – Projected Aggregate Demand and Unit Profiles Based on User Input

6.1.2 Model Assumptions and Formulation

The model that we construct below is based on the following set of assumptions:

1. Demand is a normally distributed iid random variable for each monthly period
2. Lead time is a normally distributed iid random variable for each monthly period
3. Suppliers have infinite capacity to meet demand
4. Each CDC acts independently, and thus does not include transferring materials between CDCs
5. CDC space is not a constraint for material stocking levels
6. Planned and random demand are proportionate at the individual SKU level

We confirmed that our normal distribution assumptions are reasonable because 80% of active SKUs with demand in 2011 average more than 10 units per month, which is a commonly accepted cutoff for assuming normality (Tyworth & O'Neill, 1997). Our goal was to make a simple strategic tool that provided general insights into future inventory analysis opportunities. This classic approach is found in virtually every textbook on production-inventory, operations, and logistics management (Tyworth & O'Neill, 1997). Other distributional assumptions could have been made for the demand and lead time variables, however research has shown that the normal approximation yields remarkably similar inventory policies as other distributions such as: Gaussian, Logistic, Gamma, Log-normal, and Weibull (Fortuin, 1980). We will present a sensitivity analysis of our normal assumptions in Section 6.3.9 when we apply a demand scenario based on a Gamma distribution.

Our formulation for the model was derived using notation from an inventory and production planning textbook (Silver, Pyke, & Peterson, 1998).

d_i = historical demand in period i

l_i = observed lead time in period i

$k =$ unit normal value based on desired service level

$$\overline{D} = \frac{\sum_{i=1}^{n} d_i}{n}$$

Equation 10 – Average Demand per Period

$$\sigma_d = \sqrt{\frac{\sum_{i=1}^{n}(d_i - \overline{D})}{n-1}}$$

Equation 11 – Standard Deviation of Demand per Period

$$\overline{L} = \frac{\sum_{i=1}^{n} l_i}{n}$$

Equation 12 – Average Order Lead Time per Period

$$\sigma_L = \sqrt{\frac{\sum_{i=1}^{n}(l_i - \overline{L})}{n-1}}$$

Equation 13 – Standard Deviation of Lead Time

The variables as defined yield the following formulations for each SKU at each CDC based on our assumptions:

$$\mathrm{E}(D_{LeadTime})) = E(L)E(D)$$

Equation 14 – Expected Demand over Lead Time

$$\sigma_{LeadTime} = \sqrt{E(L)\sigma_D^2 + E(D)^2\sigma_L^2}$$

Equation 15 – Standard Deviation of Demand over Lead Time

$$\mathrm{ROP} = E(D_{LeadTime}) + k\sigma_{LeadTime}$$

Equation 16 – Reorder Point

$$\mathrm{SS} = \mathrm{k}\sigma_{\mathrm{LeadTime}}$$

Equation 17 – Safety Stock

$\mathrm{EOQ} = \min(\sqrt{\frac{2\mathrm{AD}}{\mathrm{vr}}}, 2011\ Total\ Demand)$, where A is the fixed ording cost, D is annual demand, v is the cost per unit to purchase, and r is the cost of capital

Equation 18 – Economic Order Quantity

$$\mathrm{E(Average\ Inventory)} = \mathrm{k}\sigma_{\mathrm{LeadTime}} + \mathrm{Emergency\ Stock} + \frac{\mathrm{EOQ}}{2}$$

Equation 19 – Expected Average Inventory

The reasoning behind limiting the EOQ value to a maximum of 2011 total demand for a SKU was to preventing ordering excessive stock for low cost low usage items. In order to assist with the reader's understanding of the model calculations, we present an example of the model calculations here:

$$\bar{D} = 212 \text{ units per month}$$

$$\sigma_d = 97.34$$

$$\bar{L} = .508 \text{ months}$$

$$\sigma_L = .750$$

$$\mathbf{A} = \$1070$$

$$\mathbf{r} = 7.35\%$$

$$\mathbf{v} = \$322.29$$

Desired service level = 95% ➡ k=1.64

$$\mathbf{E}(D_{LeadTime})) = 212 * .508 = 107.70\ units$$

$$\sigma_{LeadTime} = \sqrt{.508 * 97.34^2 + 107.70^2 * .750^2} = 106.48$$

ROP = $107.70 + 1.64 * 106.48 = 282.32$ ➡ which rounds up to 283 units

SS = $1.64 * 106.48 = 174.62$ ➡ which rounds up to 175 units

EOQ = $\sqrt{\frac{2*1070*(212*12)}{322.29*.0735}} = 479.4$ ➡ which rounds up to 480 units

Given the inputs defined above, the inventory policy for this example SKU would be to order 480 units each time the inventory position dropped below 283 units. The model we created was developed using excel, and uses the formulations above to calculate cost minimizing inventory policies for each SKU at each CDC location based on user desired service levels. The model was developed using observed 2011 demand and lead time data to compute the average and standard deviation of demand over the expected lead time. We chose to use 2011 data so that we could compare this model to the robust model is presented in Section 6.2. Both models were developed using 2011 demand information so that we could compare them using actual demand from January to October 2012 in Section 6.3. Holding costs were estimated using a Tracks Energy's cost of capital for inventory. Fixed ordering costs were estimated by calculating estimated labor and transportation costs. Labor costs were determined by adding the total annual labor costs for inventory planners, invoice payment personnel, and warehouse receiving personnel, divided by the number of orders placed in 2011. Transportation costs were calculated by dividing the total transportation cost in 2011 by the number of orders placed in 2011.

The user of this model has the ability to modify service levels by SKU category, fixed ordering costs, variable ordering costs, and percentage of planned work in order to understand the impact of input assumptions. By changing these input variables, the model will recalculate inventory policies based on the user's preferences. We use the E(Inventory) value for comparing this model's results with historical inventory levels observed by Tracks Energy.

6.1.3 Strategic Insights

Our inventory analysis of the current state yielded the information presented in Figure 32 below. Category 'A' (2% of total active SKUs) materials account for 22% of inventory value, and 80% of annual throughput based on oversimplified inventory ordering policies. Likewise, 24% of inventory value (2% of total active SKUs) is comprised of Category 'B' material which account for 10% of annual throughput value. The largest inventory portion is Category 'C' items which account for only 10% of annual throughput.

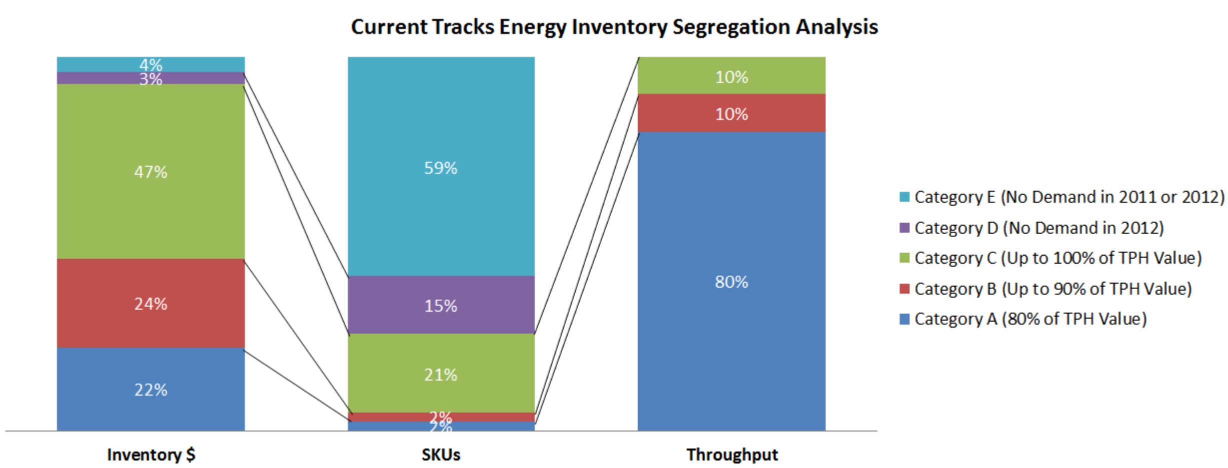


Figure 32 – Tracks Energy Inventory Value by SKU and Throughput

The revised aggregate inventory projections based on our simple, yet more sophisticated, inventory model yielded the results illustrated in Figure 33 below.

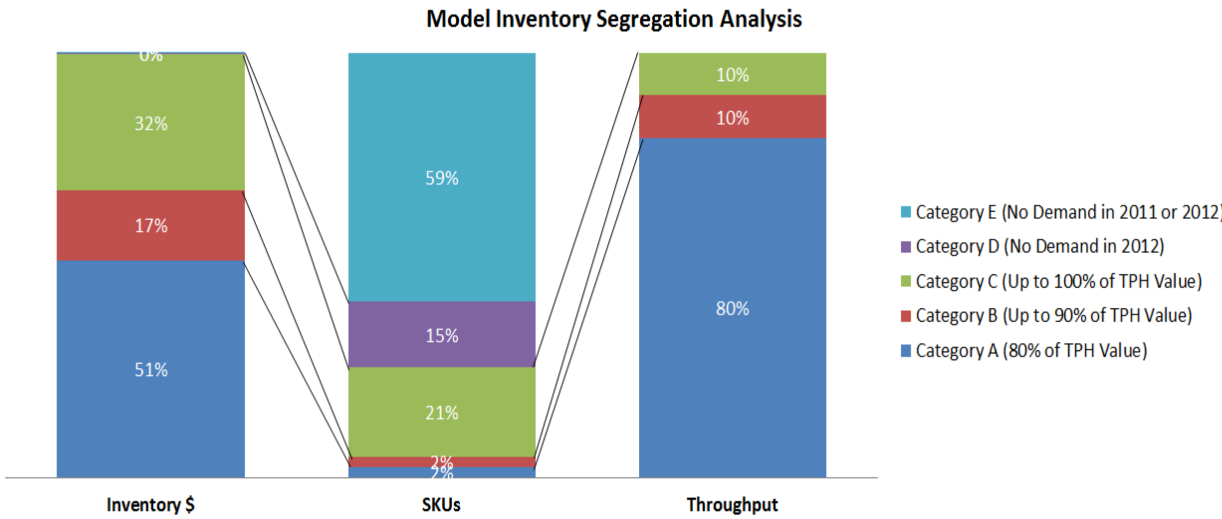


Figure 33 – Projected Tracks Energy Projected Inventory Value by SKU and Throughput

Based on current inventory fill rates, the model indicates Category 'A' items should be a larger percentage of total inventory than the current state (29% more ~$39M). The model also indicates a 7% decrease in inventory value for Category 'B' items may be possible. These insights lead us to conclude that the manual heuristics used by inventory planners may be biased, and do not appropriately recognize the importance of the high volume and/or high value of Category 'A' items over Category 'C' items.

The model also provides insight into the total inventory values by SKU. Figure 34 below shows a side by side comparison of the current and proposed aggregate inventory levels resulting from the inventory model. For this comparison, the service levels for each category were set to match the historical values from a trailing 12 month average, as indicated below.

- Category 'A' Items: 96% Fill Rate
- Category 'B' Items: 87% Fill Rate
- Category 'C' Items: 74% Fill Rate

The indications from the model are that significant savings are available through updating inventory policies to balance long term ordering and holding costs. It is important to note that the inventory values suggested by the model are representative of an upper bound for potential improvement since the normal distribution can allow negative demand values which leads to an underestimation of reorder point values. In order to help compensate for this bias, we always rounded calculated reorder points up to the next whole number.

Overall, the model indicates a potential inventory reduction of 35% is possible without changing current service levels. Inventory reductions of 54% and 56% are projected for Category 'B' and 'C' items respectively. Category 'A' inventory values recommended by the model suggest an increase of 48% is necessary to maintain current service levels. Safety stock requirements prevent a complete elimination of slow moving Category 'D' and 'E' items. Since the model was built based on historical demands, a simulation of the policies using new 2013 demand should be used to verify the model achieves expected service levels given the proposed changes to inventory policies. The internship concluded prior to the start of 2013, and thus real world data was not available to validate these estimates.

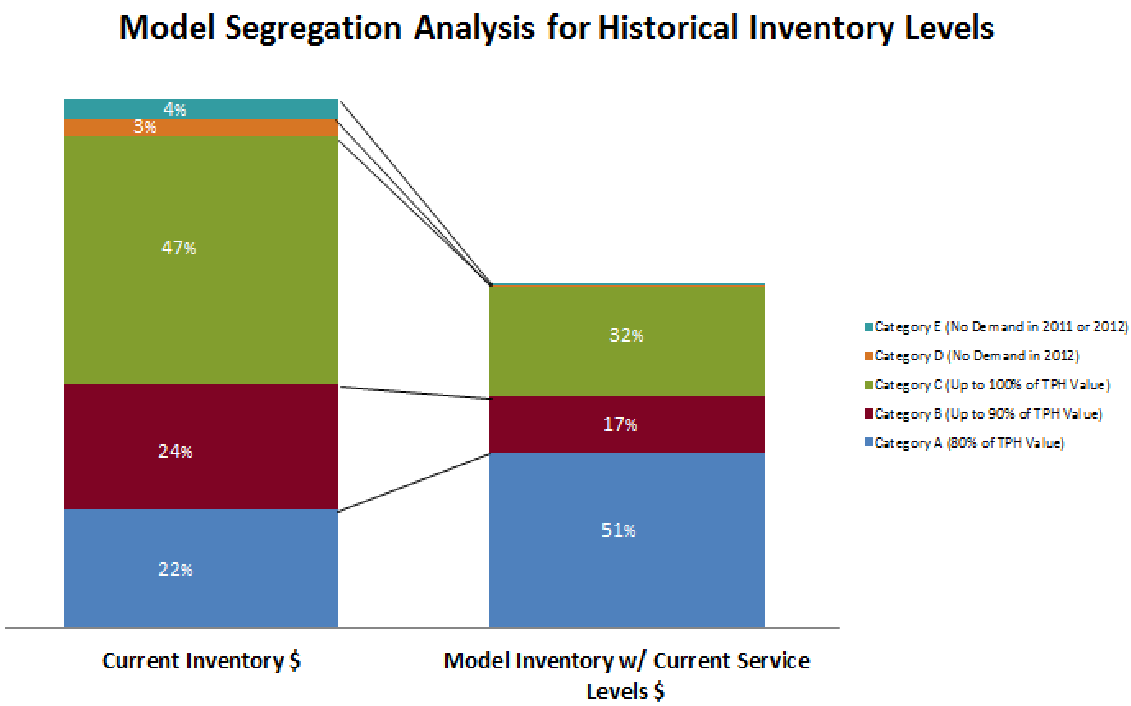


Figure 34 – Current vs. Model Inventory Value by Category

In Section 5.3.2 we projected the line fill rate would improve to the top 25 percentile for inventory performance. In order to accurately identify an upper bound for inventory savings, we modified the service levels for the inventory as follows:

- Category 'A' Items: 98% Fill Rate
- Category 'B' Items: 95% Fill Rate
- Category 'C' Items: 92% Fill Rate

After making these adjustments through the user input form in the four individual CDC models, we were able to aggregate the expected inventory levels using the new expected average inventory calculations. The result is shown in Figure 35 below. The relative distribution of materials is very similar to the distribution from the model based on historical fill rates, but we do observe a modest increase in inventory levels. In total, the new model with improved service levels indicates an inventory reduction of 27% is possible.

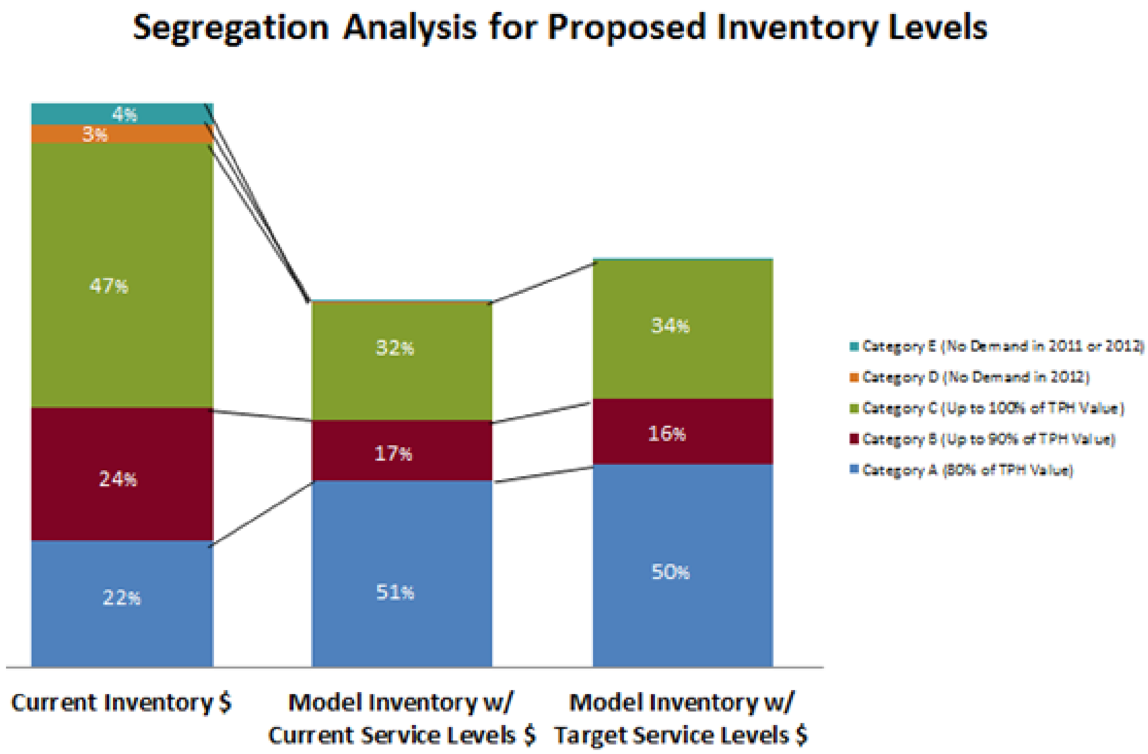


Figure 35 - Inventory Value Comparison between Current Inventory and Model Inventory Expectations

These results suggest that improved CDC fill rates with reductions in inventory are likely, based on addressing the type and quantities of materials required to support the business through more sophisticated inventory stocking policies. The implementation of SAP as the inventory management system for Tracks Energy will move the company in the right direction, but at the time of our project, it was unclear how SAP would develop its own recommended inventory stocking policies.

6.1.4 Comparing Procurement Quotes Using the Model

One of the most challenging decisions any supply chain faces is how to compare low purchase prices with increased lead times. Many organizations focus on procuring material at the lowest possible price, but they ignore the implications to total supply chain cost (mainly transportation and increased inventory holding costs). In order to help Tracks Energy avoid this pitfall, we built into our Excel model a tool that calculates the breakeven point for lead time considering inventory costs based on a given unit price. The user interface for this tool is shown in Figure 36 below. The user selects a SKU from a dropdown menu in the top left hand corner of the interface, and then inputs a new price, lead time, order quantity, or average demand. The tool calculates the total expected cost based on the new information, which allows the user to compare different quotes from different vendors to determine which option has the lowest expected total cost, not just the lowest purchase cost. This tool will be important when trying to evaluate the total cost associated with procuring materials from low cost countries.

SKU Information

Item ID	Item Description	Category	Vendor	UOM	Status
0810389	BRACE, XARM, FLAT, WOOD, 26IN. CTR TO CTR	B	A	6.94	PR

Inventory Policy Information

Modified EOQ	Model Average Demand/Mo.	Empirical Average Lead Time	Empirical STDEV Lead Time	Model Standard Deviation of Demand	Std Price
3099	191	7	4	261	$ 6.94

Inventory Policy Costs

E(Holding Costs)	E(Ordering Costs)	Total Cost	E(Orders/Year)	Value of Emergency Stock
$ 1,629.55	$ 790.45	$ 2,420.00	0.74	$ 10,410.00

Modified Policy Costs

Modified EOQ	Model Average Demand/Mo.	Average Lead Time	Standard Deviation of Lead Time	Model Standard Deviation of Demand	New Std Price
3099	191	30	4	261	$ 6.50

E(Holding Costs)	E(Ordering Costs)	Total Cost	E(Orders/Year)	Value of Emergency Stock
$ 1,598.37	$ 790.45	$ 2,388.82	0.74	$ 10,410.00

Figure 36 – Calculation Tool for Evaluating Total Supply Chain Costs

In this section we applied a common framework for inventory policy development based on stochastic demand and lead time using normal approximations. Many companies use this type of policy for their daily stocking activities, but we do not view this as a tactical tool for Tracks Energy at this point. The inventory policies developed were based on historical demand instead of future demand forecasts. While there is value in the insights discussed, further evaluation of these policies in a future state, which was not used to calculate the policies, is necessary to verify the policies will work as intended from a tactical point of view.

6.2 Robust Optimization Approach

Since Tracks Energy is more concerned about service level than it is about total cost, a robust optimization formulation may fit well with the goals of the organization. The robust formulation presented in this thesis is designed to minimize total supply chain costs given the possibility of unfavorable demand realization. The formulation presented here includes the concept of economic transshipments.

6.2.1 Model Assumptions and Formulation

The model that we constructed is based on the following set of assumptions:

1. Lead time is 0
2. Demand does not follow a predefined probability distribution
3. Suppliers have infinite capacity to meet demand
4. CDCs are able to leverage economic transfers to minimize ordering costs
5. CDC space is not a constraint for material stocking levels
6. Planned and random demand are proportionate at the individual SKU level

A few of the assumptions of this model are different than the assumptions of the model presented in Section 6.1. First, this model assumes that lead time is 0. Second, in this model demand is not restricted to a specific probability distribution. Finally, this model allows economic transfers between CDCs in order to decrease fixed ordering costs when it is beneficial to do so.

We will use the following notation for the decision variables of the optimization problem:

- u_{it} are the units ordered from warehouse i at time t
- z_{it} are the units transshipped from warehouse i to warehouse j at time t
- y_{it} denotes the holding costs, or backlogging costs, incurred in warehouse i at time t
- v_{it} is a binary variable that will take value 1 if an order is placed from warehouse i at time t, and 0 otherwise

The input data for the model is defined by the following:

- x_i^0 is the initial stock available in warehouse i at time t
- c_i is the per unit ordering cost at warehouse i
- h_i is the per unit holding cost at warehouse i
- b_i is the per unit backlogging cost at warehouse i
- a_{ij} is the per unit transshipment costs from warehouse i to warehouse j
- K_i is the fixed ordering costs at warehouse i

We will begin our formulation by adapting the formulation of Bertsimas and Thiele (2006) to include transshipments. The resulting formulation is as follows:

Objective Function: Minimize total inventory costs

$$\min_{i,j,t} \sum_i \sum_t \left(K_i v_{it} + c_{it} u_{it} + y_{it} + \sum_{j \neq i} a_{ij} z_{ijt} \right)$$

Where

- $K_i v_{it}$ represents the fixed cost of ordering
- $c_{it} u_{it}$ represents the unit ordering costs
- y_{it} represents the holding and backlogging costs
- $a_{ij} z_{ijt}$ represents the cost of transferring units

Subject to the following constraints:

- Holding costs are greater than or equal to the initial inventory plus the (positive) difference between orders and demand plus units transferred out

$$y_{it} \geq h_i \left(x_i^0 + \sum_{l=1}^{t} \left(u_{il} - d_{il} + \sum_{j \neq i} (z_{jil} - z_{ijl}) \right) \right)$$

Equation 20 – Holding Costs with transfers

- Backlog costs are greater than or equal to the initial inventory plus the (negative) difference between orders and demand plus units transferred in

$$y_{it} \geq -b_i \left(x_i^0 + \sum_{l=1}^{t} \left(u_{il} - d_{il} + \sum_{j \neq i} (z_{jil} - z_{ijl}) \right) \right)$$

Equation 21 – Backlog Costs with transfers

- Transfers are greater than or equal to 0

$$z_{ijt} \geq 0, \forall i, j \neq i, t$$

Equation 22 – Number of Transfers

- Orders are greater than or equal to 0

$$u_{it} \geq 0, \forall i, t$$

Equation 23 – Units Ordered

- A binomial variable is defined (v_{it}) to track number of orders ($v_{it} = 1$ if an order is placed)

$$v_{it}M \geq u_{it} \ \forall i, t$$

Equation 24 – Number of Orders

- M represents a very large number such that it is always larger than the number of possible units ordered

$$v_{it} \in \{0,1\} \ \forall i, t$$

Equation 25 – Binary variable for tracking orders

Where the uncertainty sets considered are defined by:

- Demand is bounded by average demand plus a multiple of standard deviations. Γ_{it} represents an aggregate uncertainty level over each period in the model, above and beyond the mean and standard deviation inputs. Γ_{it} provides users of this model a lever to control the level of certainty (e.g. forecast accuracy), which provides an additional level of potential conservatism regarding model policies. Over time, Γ_{it} should be increasing through the periods of the model representing an increase in overall uncertainty.

$d_{it} = \bar{d}_{it} + \sigma_{it}w_{it}$ in an uncertainty set $U_{it} = \{w_{it}: |w_{it}| \leq 1 \ \forall i, t, \sum_{l=1}^{t}|w_{il}| \leq \Gamma_{it}\}$

The uncertainty set restrictions prevent this formulation, as we have presented it, from being solved in one optimization program. In order to convert this optimization formulation into a form we can solve with one optimization program, we must solve for a dual formulation, which provides an alternative expression to the optimal value of the original constraints. Solving the dual formulation allows us to include the constraints for the uncertainty set U_{it} in the holding cost and backlogging cost constraints (Equation 20 and Equation 21 respectively).

The concept of duality states that for a primal problem (e.g. Maximize $\mathbf{c}^T\mathbf{x}$ subject to $A\mathbf{x} \leq \mathbf{b}$, $\mathbf{x} \geq 0$), there is a corresponding symmetric dual problem (e.g. Minimize $\mathbf{b}^T\mathbf{y}$ subject to $A^T\mathbf{y} \geq \mathbf{c}$, $\mathbf{y} \geq 0$). In order to develop the dual for our primal formulation we need to define two dual variables:

- q_{it} will be associated with $\sum_{l=1}^{t}|w_{il}| \leq \Gamma_{it}$
- r_{ilt} will be associated with $|w_{it}| \leq 1$

The worst case for Equation 20 (holding costs) occurs when the realized demands (d_{il}) are very small, independent of the quantity ordered. We can solve for the smallest possible demands given our uncertainty set with the following optimization problem:

$$\min_{w_{il}} \sum_{i=1}^{n} \sum_{l=1}^{t} \bar{d}_{il} + \sigma_{il} w_{il}$$

$$s.t. \; \sum_{l=1}^{t} |w_{il}| \leq \Gamma_{it}$$

$$|w_{il}| \leq 1$$

We can see from this set of equations that the smallest possible demand value occurs at the lower bound of w_{il}, which we will refer to as $\underline{w_{il}}$. Any value for w_{il} larger than the lowest possible value will result in a larger demand value, lower holding costs, and will take away from the total budget of uncertainty (Γ_{it}). Thus, $\underline{w_{il}}$ is the optimal solution to this auxiliary optimization problem.

Conversely, the worst case for Equation 21 (backlog costs) occurs when the demands realized (d_{il}) are very large. We can solve for the largest possible demand values given our uncertainty set with the following optimization problem:

$$\max_{w_{il}} \sum_{i=1}^{n} \sum_{l=1}^{t} \bar{d}_{il} + \sigma_{il} w_{il}$$

$$s.t. \; \sum_{l=1}^{t} |w_{il}| \leq \Gamma_{it}$$

$$|w_{il}| \leq 1$$

We can see from this set of equations that the largest possible demand value occurs at the upper bound of w_{il}, which we will refer to as $\overline{w_{il}}$. Any value for w_{il} smaller than the largest possible value will result in a smaller demand value, and lower backlog costs. Thus, $\overline{w_{il}}$ is the optimal solution to this second auxiliary optimization problem.

Since $\overline{w_{il}} = -\underline{w_{il}}\ \forall i, l$, both of these auxiliary problems yield equivalent values for $|w_{il}|$, we can solve for the optimal solution to one of the problems, and get the optimal solution to the other problem.

The formulation for backlog costs can be written without the $|w_{il}|$ because $\sigma_{il} \geq 0\ \forall i, l$. An equivalent expression for the worst case scenario for backlog costs is the following:

$$\max_{w_{il}} \sum_{i=1}^{n} \sum_{l=1}^{t} \sigma_{il} w_{il} + \sum_{l=1}^{t} \bar{d}_{il}$$

$$s.t. \ \sum_{l=1}^{t} w_{il} \leq \Gamma_{it}$$

$$w_{il} \leq 1$$

Using the standard rules to construct the dual problem (Bertisimas & Tsitsiklis, 1997), we can develop an equivalent expression to solve for the worst case scenario backlog costs. By extension, the same formulation is an equivalent expression for the worst case scenario for holding costs. By the strong duality theorem (Bertisimas & Tsitsiklis, 1997), the optimal value of the dual problem is also the optimal value of the worst case backlog cost formulation. By incorporating the previously defined dual variables (q_{it} and r_{ilt}), the dual of the backlog cost optimization problem can be written as:

$$\min_{l} q_{it} * \Gamma_{it} + \sum_{l=1}^{t} r_{itl}$$

$$s.t.\ r_{itl} + q_{it} \geq \sigma_{il}$$

$$r_{itl} \geq 0$$

$$q_{it} \geq 0$$

The resulting formulation of our linear program is as follows:

Objective Function: Minimize total inventory costs

$$\min_{i,j,t} \sum_{i} \sum_{t} \left(K_i v_{it} + c_{it} u_{it} + y_{it} + \sum_{j \neq i} a_{ij} z_{ijt} \right)$$

Where

- $K_i v_{it}$ represents the fixed cost of ordering
- $c_{it} u_{it}$ represents the unit ordering costs
- y_{it} represents the holding and backlogging costs
- $a_{ij} z_{ijt}$ represents the cost of transferring units

Subject to the following constraints:

- Holding costs are greater than or equal to the initial inventory plus the (positive) difference between orders and demand plus units transferred out. Note the new formulation contains the objective function of the dual formulation.

$$y_{it} \geq h_i \left(x_i^0 + \Gamma_{it} q_{it} + \sum_{l=1}^{t} r_{ilt} + \sum_{l=1}^{t} \left(u_{il} - \bar{d}_{il} + \sum_{j \neq i} (z_{jil} - z_{ijl}) \right) \right) \forall\ i, t$$

Equation 26 – Dual LP Holding Costs with transfers

- Backlog costs are greater than or equal to the initial inventory plus the (negative) difference between orders and demand plus units transferred in. Note the new formulation contains the objective function of the dual formulation.

$$y_{it} \geq -b_i \left(x_i^0 + \Gamma_{it} q_{it} + \sum_{l=1}^{t} r_{ilt} + \sum_{l=1}^{t} \left(u_{il} - \bar{d}_{il} + \sum_{j \neq i} (z_{jil} - z_{ijl}) \right) \right) \forall\ i, t$$

Equation 27 – Dual LP Backlog Costs with transfers

- Transfers are greater than or equal to 0

$$z_{ijt} \geq 0, \forall i, j \neq i, t$$

Equation 28 – Dual LP Number of Transfers

- Orders are greater than or equal to 0

$$u_{it} \geq 0, \forall i, t$$
Equation 29 – Dual LP Units Ordered

- A binomial variable is defined (v_{it}) to track number of orders ($v_{it} = 1$ if an order is placed)

$$v_{it}M \geq u_{it} \ \forall i, t$$
Equation 30 – Dual LP Number of Orders

- M represents a very large number such that it is always larger than the number of possible units ordered

$$v_{it} \in \{0,1\} \ \forall i, t$$
Equation 31 – Dual LP Binary variable for tracking orders

- M represents a very large number such that it is always larger than the number of possible units ordered

$$q_{it} + r_{ilt} \geq \sigma_{il} \ \forall i, t; \ \forall l \leq t$$
Equation 32 – 1st Dual Constraint

- M represents a very large number such that it is always larger than the number of possible units ordered

$$q_{it} \geq 0 \ \forall i, t$$
Equation 33 – 2nd Dual Constraint

- M represents a very large number such that it is always larger than the number of possible units ordered

$$r_{ilt} \geq 0 \ \forall i, t\,; \forall l \leq t$$
Equation 34 – 3rd Dual Constraint

The goal of robust optimization is to optimize total ordering, holding, backlogging, and transfer costs given possible demand scenarios. Figure 37 below shows a bounded demand scenario for a 3 CDC network. Average demand (μd) is in the center of the cube, and the corners of the cube represent the extremes of μd-z σd and μd+zσd for each CDC in each period. The size and shape of the bounded area is dependent on the mean demand, the uncertainty level defined by zσd, and the total uncertainty bound of Γ. In each period, the demand for an item at each CDC is allowed to be either large (+) or small (-). The optimization presented here determines the lowest possible cost given the most unfavorable potential demand scenarios.

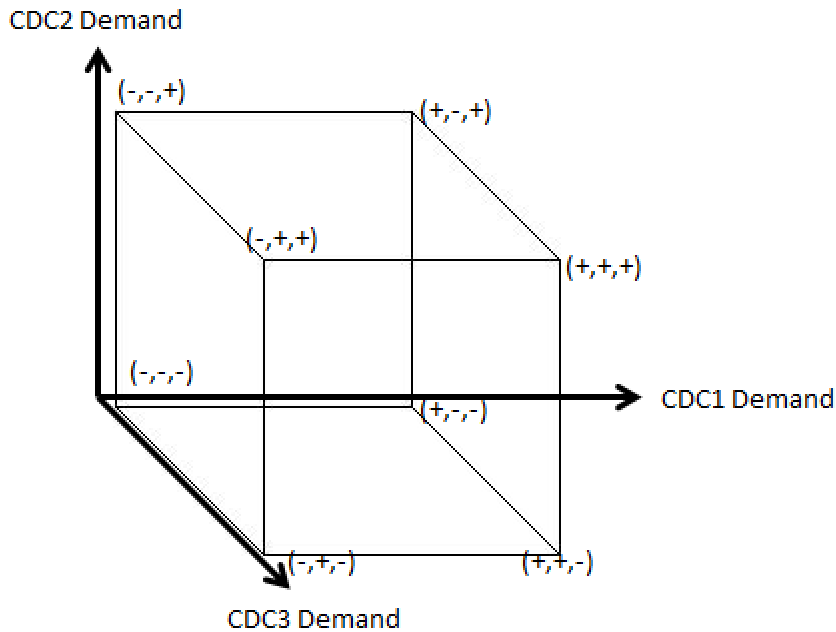


Figure 37 – Representation of Bounded Demand Area for Robust Model

The model we built was designed to run in the AMPL solver tool. We selected a 10 period scenario to coincide with the 10 months of observed demand we had for each SKU in 2012. We used a 3 CDC network to simplify the calculations. In order to take advantage of the model's ability to vary average demand and standard deviation by period, we divided historical demand into four quarters. For each CDC, we used the average demand observed from January-March in 2011 and 2012 as the average demand for Q1. Likewise, we used the standard deviation of the observed demand over the same period as the standard deviation of demand in Q1. We followed an identical process to determine the average and standard deviation of demand for Q2, Q3 and Q4. In the model, standard deviation and average demand for periods 1-3 corresponded with Q1, 4-6 with Q2, 7-9 with Q3, and period 10 with Q4. An example of the average demand standard deviation input for the model is shown in Figure 38 below. In this example the standard deviation of demand from January 2011 – March 2011 was 1 unit at CDC 1, 2 units at CDC2 and 0 units at CDC3. The model uses the Q1 standard deviation of demand for the first three periods of the model as indicated above.

sigma_w:	1	2	3
1	1	2	0
2	1	2	0
3	1	2	0
4	1	13	1
5	1	13	1
6	1	13	1
7	4	12	4
8	4	12	4
9	4	12	4
10	4	1	2

Figure 38 – Example Standard Deviation input for a Single SKU with 3 CDCs and 10 Periods

6.2.2 Strategic Model Insights

The robust model is a mixed integer program that captures economic transfers, but not emergency transfers. Because this model makes all optimization decisions at the time demand is realized, it only uses transfers to reduce fixed ordering costs. As one would expect, the output of this model is heavily dependent on the costs associated with transferring units relative to the fixed ordering costs. The resulting outputs of the model will fall into two categories:

1. The cost of ordering units into a single CDC and then transferring to the other two CDCs is more cost effective than each CDC ordering independently
2. The cost of ordering units into a single CDC and then transferring is more expensive than each CDC ordering independently.

To illustrate the dependency on the relationship between ordering costs and transfer costs represented by the first type of output, we present Figure 39 below.

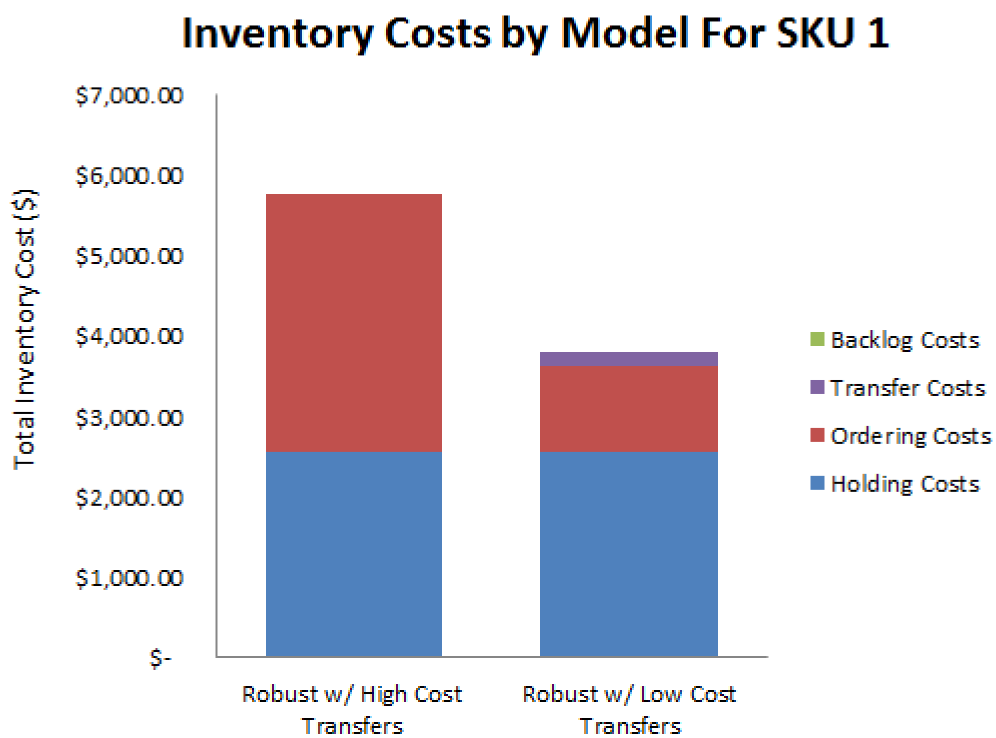


Figure 39 – SKU 1 Robust Model Costs Comparing High and Low Cost Transfers

	Unit Cost	Holding Cost	Backlog Cost	Low Transfer Cost	High Transfer Cost	Fixed Order Cost
CDC1	227.12	$ 1.35	$ 245.14	$ 2.69	$ 56.78	$ 1,070
CDC2	227.12	$ 1.35	$ 245.14	$ 2.69	$ 56.78	$ 1,070
CDC3	227.12	$ 1.35	$ 245.14	$ 2.69	$ 56.78	$ 1,070

Figure 40 – Robust Model Inputs for SKU 1

In Figure 39 we display a Category 'B' SKU with the inputs depicted in Figure 40. The low value for transfer costs was double the value of holding costs, and the high value of transfer costs was set to 25% of the unit cost. These values were selected because they would guarantee the backlogging costs were larger than the holding costs, and also so the ratios would be consistent between high and low transfer costs. We held this formulation for high and low transfer costs consistent for all of the SKUs sampled. The results show us that with a low transfer cost, the model utilizes economic transfers to minimize total cost. In fact, the model ordered all of the required units through the CDC with the largest potential demand, and transferred units to the other two warehouses so to avoid fixed costs of ordering. When the transfer cost increases unfavorably as compared to ordering costs, the model ignores transfers and orders for each CDC independently. The result is an increase in ordering costs as each CDC since each facility orders independently. The threshold for where this type of event occurs is dependent on the inputs for each SKU, and is not directly relatable to a ratio between ordering costs and transfer costs. Figure 41 below shows the inventory holding costs per period for high and low level cost of transfers for SKU 1. With low cost transfers, the model made a single purchase for one CDC, and then transferred units to the other two CDCs. The same model formulation with high cost transfers placed a single order for each CDC in the first period. This result aligned with our intuition that the ability to transfer inventory reduces inventory holding costs by allowing demand risk to be pooled across locations.

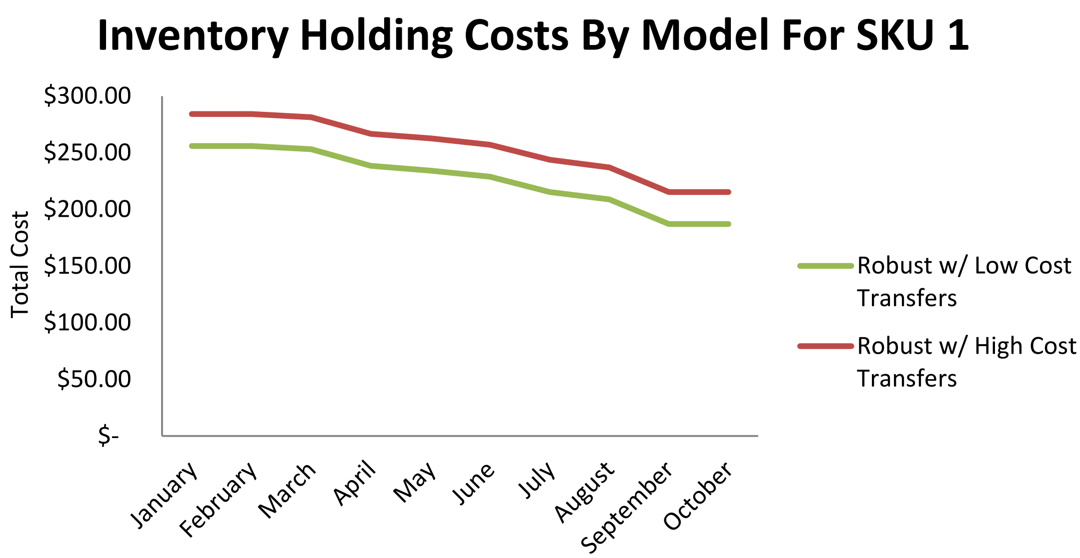


Figure 41 – Robust Model Holding Costs for SKU 1

The second potential output of the model occurs when low transfer costs are unfavorable compared to ordering costs, making the costs of transferring material irrelevant. We demonstrate this result using a high volume Category ‘A’ SKU with a high per unit cost. Figure 42 below shows the resulting output costs for SKU 3, an example when low transfer costs are unfavorable compared to fixed ordering costs. Since the volume of units that would need to be transferred, if all of the units were ordered through a single building, would exceed the costs of each building acting independently, the model did not suggest transfers. The per period holding costs in Figure 44 show that the model outputs are identical for both low and high transfer costs.

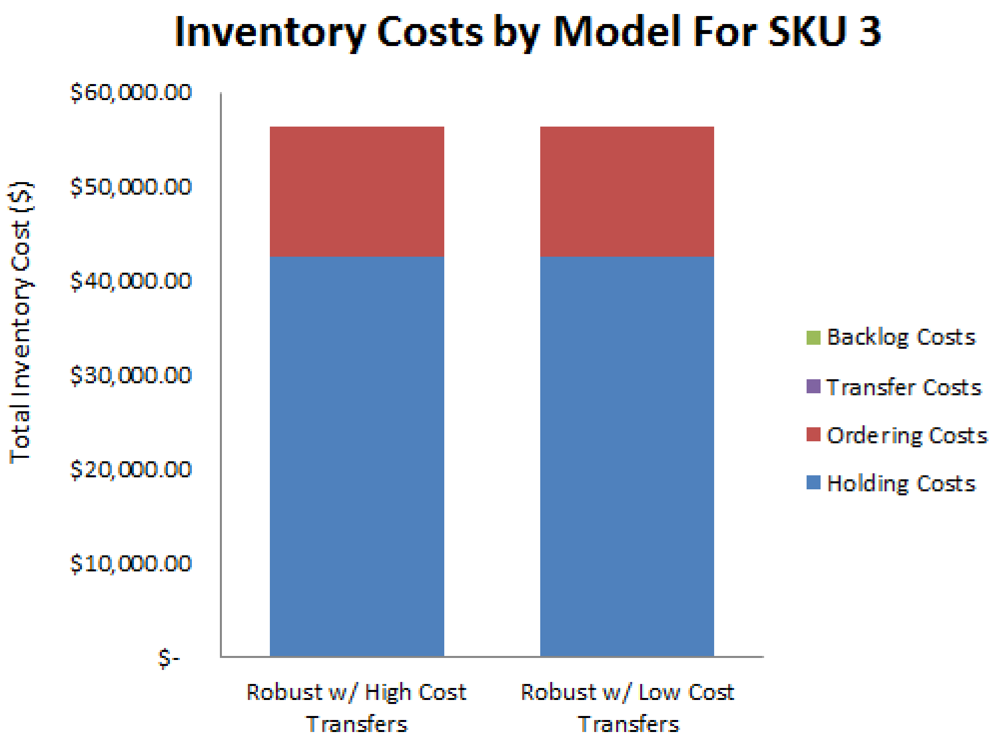


Figure 42 - SKU 3 Robust Model Costs Comparing High and Low Cost Transfers

	Unit Cost	Holding Cost	Backlog Cost	Low Transfer Cost	High Transfer Cost	Fixed Order Cost
CDC1	322.29	$ 1.91	$ 347.86	$ 3.82	$ 80.57	$ 1,070
CDC2	322.29	$ 1.91	$ 347.86	$ 3.82	$ 80.57	
CDC3	322.29	$ 1.91	$ 347.86	$ 3.82	$ 80.57	

Figure 43 - Robust Model Inputs for SKU 3

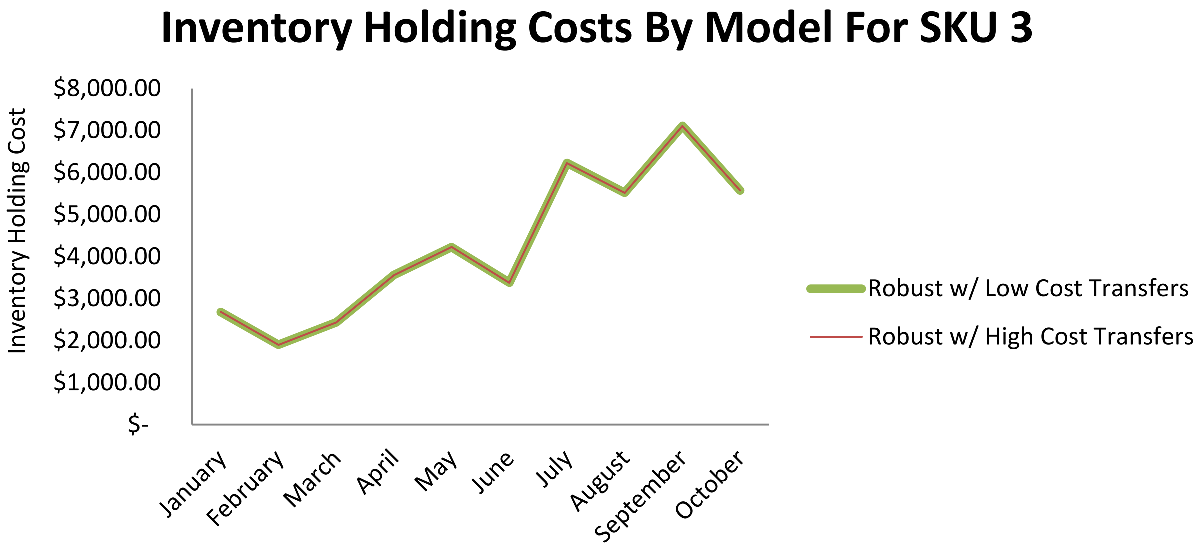


Figure 44 - Robust Model Holding Costs for SKU 3

We ran the model with several different SKUs from a variety of SKU categories, demand volumes and unit costs. The entire set of model outputs fell into one of the two categories presented above, so we do not repeat the results in this section. More examples are presented in Section 6.3 when we compare the results of this model with the model presented in Section 6.1.

One important thing to note about this model is that at the beginning of the time horizon it is designed to make decisions for all demand periods. This model attempts to minimize long term ordering, holding costs, and transfer costs over the entire time horizon given varying levels of demand uncertainty in each period. The emphasis of this model on planning for unfavorable demand scenarios demonstrates that (s,Q) ordering policies are not optimal, as indicated by varying orders based on potential demand scenarios in each period. There are two scenarios that we believe this type of model would suit Tracks Energy well: (1) Evaluating inventory prior to storm season, and (2) annual procurement planning for deciding contract quantities. In both of these scenarios, future expectations for demand have significant impacts to optimal ordering quantities. Since Tracks Energy cannot choose to stock out of an item, and interrupt service, we believe this type of unfavorable demand planning model may be well suited for their particular needs.

6.3 Comparing the Robust Model and the Simple Model

In this section we will compare individual SKU inventory costs estimated from each of the models presented in Sections 6.1 and 6.2. The model from Section 6.1 will be referred to as the “simple” model, and the model from Section 6.2 will be referred to as the “robust” model through the remainder of this document. We will discuss the strengths and weaknesses of each model as indicated by the data analysis presented in this section. We will present 5 representative SKUs (2 Category ‘A’, 2 Category ‘B’ and 1 Category ‘C’) to highlight overall performance between the models. Finally, we will summarize our findings from our comparison.

In order to make the comparison of these two models as fair as possible, we began each scenario (t=0) with 0 inventory. This starting point will force each model to order inventory in the first period, which will make costs associated with ordering materials directly attributable to the respective models. In order to have the simple model emulate the robust model, the lead times for all SKUs were set to 0. This dramatically reduced the reorder points associated with each SKU in the simple model. The transfer, ordering, holding, and backlogging costs were identical for each SKU in both scenarios. For our observed demand string, we used estimated project/program demand from 2012. The results by SKU are shown in the following sections.

6.3.1 Simple vs. Robust Comparison SKU 1

The first SKU we present is a locking cap with a 1” vent. The purchase price of the item is $227.12, and the monthly average demand from 2011 to 2012 was 22 units per month. This SKU is a Category ‘B’ item based on the classifications presented at the beginning of this chapter.

Simple Model outputs used for the comparison are:

- Reorder points for CDC1, CDC2, and CDC3 were 4, 5, and 2 respectively.
- The EOQ values for each CDC were 8, 52, and 9 respectively

Robust Model Inputs are:

	Unit Cost	Holding Cost	Backlog Cost	Low Transfer Cost	High Transfer Cost	Fixed Order Cost
CDC1	$ 227.12	$ 1.35	$ 245.14	$ 2.69	$ 56.78	$ 1,070
CDC2	$ 227.12	$ 1.35	$ 245.14	$ 2.69	$ 56.78	$ 1,070
CDC3	$ 227.12	$ 1.35	$ 245.14	$ 2.69	$ 56.78	$ 1,070

The resulting ordering and transferring decisions are presented in Table 1 below:

	Demand			Simple Model Orders			Low Transfer Cost Robust Model Orders			High Transfer Cost Robust Model Orders			Low Transfer Cost Robust Model Transfers			High Transfer Cost Robust Model Transfers		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	8	52	9	0	212	0	39	125	48	23	-71	48	0	0	0
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	9	0	0	0	0	0	0	5	-5	0	0	0	0
Period 9	1	12	3	8	0	0	0	0	0	0	0	0	11	-11	0	0	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1 –Ordering Decisions and Transfers for SKU1

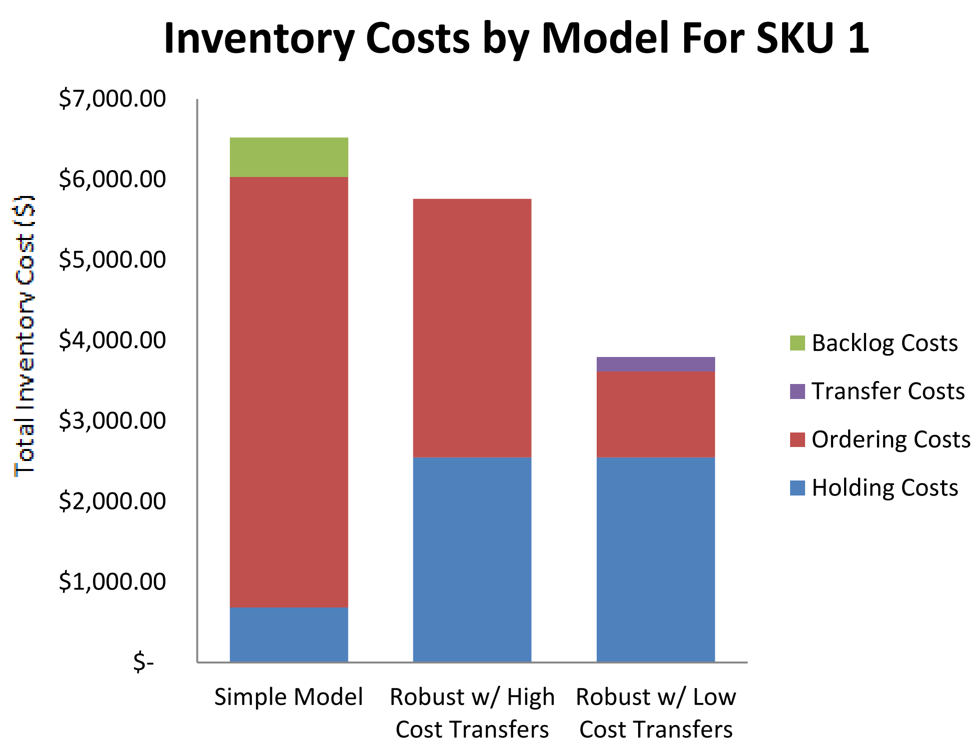


Figure 45 – Inventory Model Total Cost Comparison for SKU 1

Figure 45 above shows that in our 10 period scenarios, both versions of the robust model had lower total expected costs than the simple model. The robust model is designed to order explicitly for the

10 period scenario, while the simple model is designed to order material over an infinite horizon. Even though the simple model is designed to balance ordering costs with holding costs, it was heavily weighted with ordering costs over the short term. The simple model failed to supply two units, resulting in the backlog costs shown in green. The robust model with high transfer costs ordered for each CDC independently, and avoided any stock outs based on planning for unfavorable demand. In both robust models all of the units were ordered at the beginning of the time horizon, but the robust model with low cost transfers avoided ordering costs by utilizing transfers. The low transfer cost robust model ordered all of the units required through a single CDC, and then took advantage of low transfer costs to balance inventory across the network.

Figure 46 below shows both versions of the robust formulation favor high inventory levels, which result in high inventory holding costs. This is to be expected since the robust model is designed to perform well given unfavorable demand. Both robust models ordered 212 units in the first period, resulting in identical holding costs (the red and green lines are perfectly aligned in Figure 46). The average inventory for the simple model was more stable, but the model was penalized for the costs associated with placing multiple orders in the short run. Both models ignore space constraints, which would need to be considered to determine policies applicable for Tracks Energy.

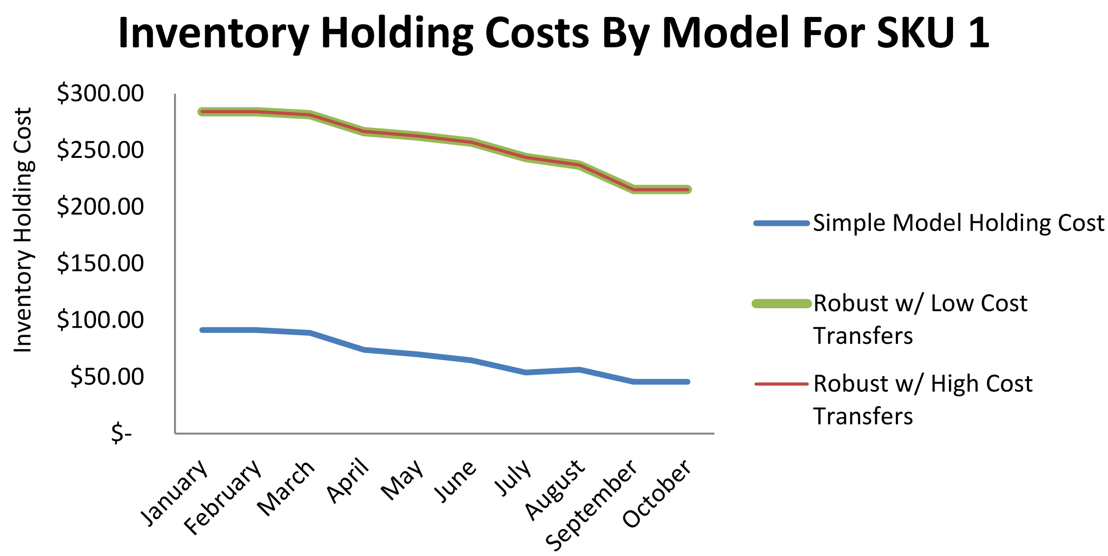


Figure 46 – SKU 1 Holding Costs for Robust vs. Simple Model Comparison

6.3.2 Simple vs. Robust Comparison SKU 2

The second SKU we present is another locking cap with a 1" vent. The purchase price of the item is $233.56, and the monthly average demand from 2011 to 2012 was 26 units per month. This SKU is a Category 'B' item based on the classifications presented at the beginning of this chapter.

Simple Model outputs used for the comparison are:

- Reorder points for CDC1, CDC2, and CDC3 were 5, 5, and 2 respectively.
- The EOQ values for each CDC were 26, 91, and 11 respectively

Robust Model Inputs are:

	Unit Cost	Holding Cost	Backlog Cost	Low Transfer Cost	High Transfer Cost	Fixed Order Cost
CDC1	$ 233.56	$ 1.38	$ 252.09	$ 2.77	$ 58.39	$ 1,070
CDC2	$ 233.56	$ 1.38	$ 252.09	$ 2.77	$ 58.39	$ 1,070
CDC3	$ 233.56	$ 1.38	$ 252.09	$ 2.77	$ 58.39	$ 1,070

The resulting ordering and transferring decisions are presented in Table 2 below:

	Demand			Simple Model Orders			Low Transfer Cost Robust Model Orders			High Transfer Cost Robust Model Orders			Low Transfer Cost Robust Model Transfers			High Transfer Cost Robust Model Transfers		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	0	1	26	91	11	0	118	0	76	149	33	5	-9	4	0	0	0
Period 2	0	2	1	0	0	0	0	0	0	0	0	0	21	-38	17	0	0	0
Period 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	2	3	2	0	0	0	0	0	0	0	0	0	11	-20	9	0	0	0
Period 6	5	1	1	0	0	0	0	140	0	0	0	0	11	-32	21	0	0	0
Period 7	1	4	0	0	0	0	0	0	0	0	0	0	56	-56	0	0	0	0
Period 8	7	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	5	14	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	2	17	1	0	0	0	0	0	0	0	0	0	0	-2	2	0	0	0

Table 2 - Ordering Decisions and Transfers for SKU2

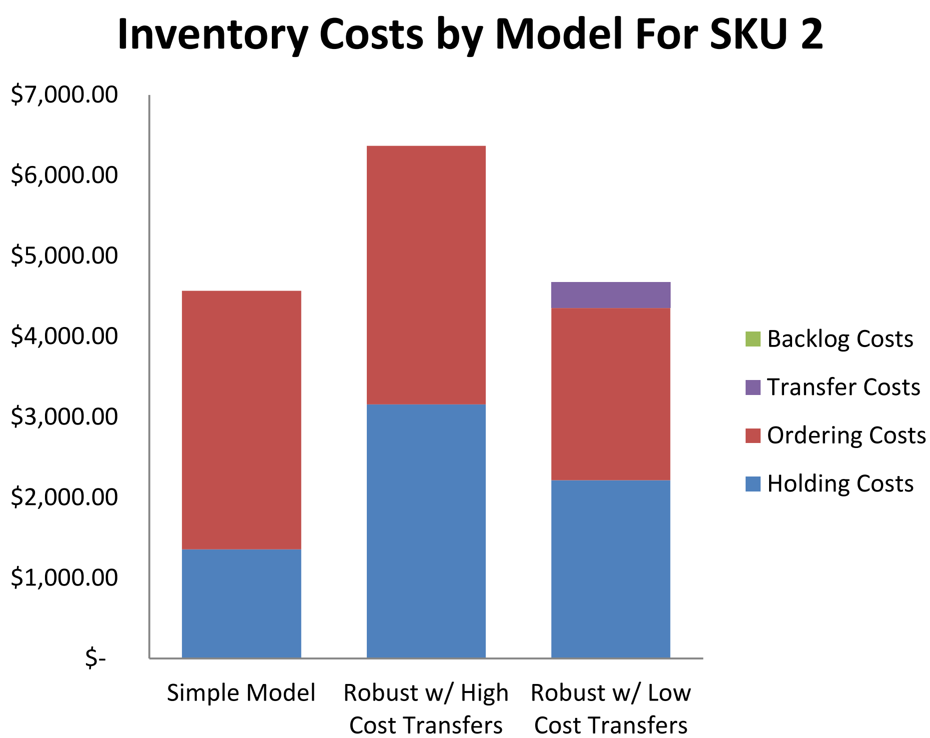


Figure 47 – Inventory Model Total Cost Comparison for SKU 2

Figure 47 above shows that the simple model policies yielded the lowest total cost over our 10 period time horizon. Both the simple model and the high cost transfer model placed at single order at each CDC at the start of the time horizon, without any orders in the subsequent periods. The low cost transfer model placed two separate orders, one in the first period and one in the sixth period. The low cost model includes transfers in the first and sixth periods, however the projected transfers in the sixth period were not needed. Because the 2012 actual demand that was used did not deplete the entire available inventory at any of the CDCs through the first 5 periods, the transfers suggested by the robust model in the sixth period were not required. Similar to the results we saw with SKU1, both robust models held significantly more inventory than the simple model.

Figure 48 below shows both versions of the robust formulation suggested larger inventory reserves, resulting in higher inventory holding costs. The standard deviation of demand in Q3 and Q4 of the robust model were significantly higher than Q1 and Q2, which resulted in a sharp increase in inventory for the low cost transfer model half way through the 10 simulated periods. The robust model with high transfer costs seemed to mimic the stocking levels of the simple model, but at a higher level due to demand uncertainty assumptions.

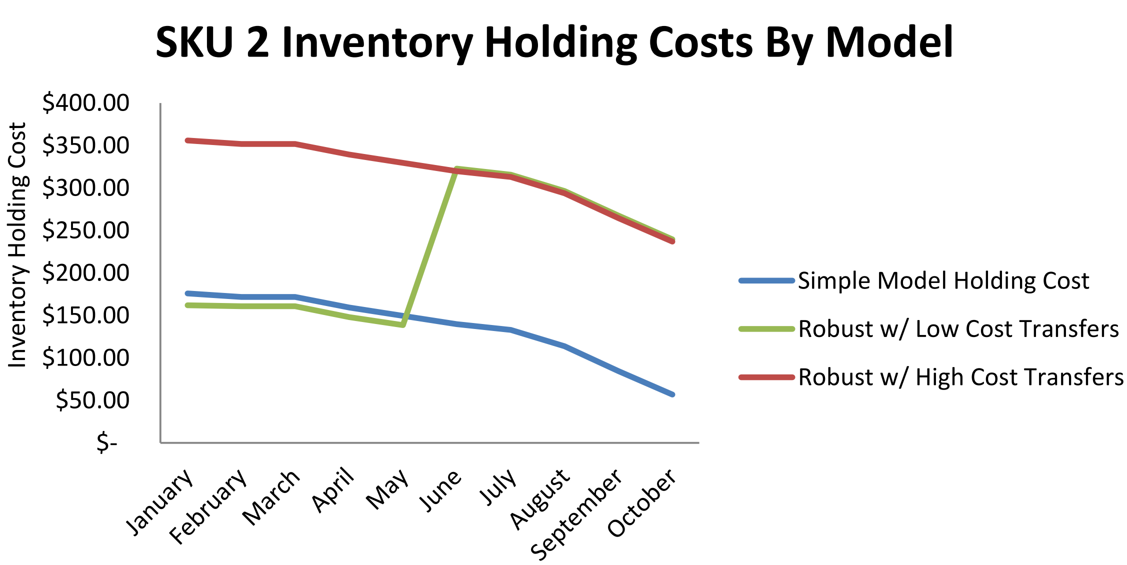


Figure 48 – SKU 2 Holding Costs for Robust vs. Simple Model Comparison

6.3.3 Simple vs. Robust Comparison SKU 3

The third SKU we present is a 40' class 3 pole. The purchase price of the item is $322.29, and the monthly average demand from 2011 to 2012 was 656 units per month. This SKU is a Category 'A' item based on the classifications presented at the beginning of this chapter.

Simple Model outputs used for the comparison are:

- Reorder points for CDC1, CDC2, and CDC3 were 201, 315, and 181 respectively.
- The EOQ values for each CDC were 392, 508, and 385 respectively

Robust Model Inputs are:

	Unit Cost	Holding Cost	Backlog Cost	Low Transfer Cost	High Transfer Cost	Fixed Order Cost
CDC1	$ 322.29	$ 1.91	$ 347.86	$ 3.82	$ 80.57	$ 1,070
CDC2	$ 322.29	$ 1.91	$ 347.86	$ 3.82	$ 80.57	$ 1,070
CDC3	$ 322.29	$ 1.91	$ 347.86	$ 3.82	$ 80.57	$ 1,070

The resulting ordering and transferring decisions are presented in Table 3 below:

	Demand			Simple Model Orders			Low Transfer Cost Robust Model Orders			High Transfer Cost Robust Model Orders			Low Transfer Cost Robust Model Transfers			High Transfer Cost Robust Model Transfers		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	35	242	117	392	508	385	432	798	567	432	798	567	0	0	0	0	0	0
Period 2	145	133	130	0	508	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	130	232	95	0	0	385	0	735	0	0	735	0	0	0	0	0	0	0
Period 4	155	207	192	392	0	0	589	0	556	589	0	556	0	0	0	0	0	0
Period 5	87	188	83	0	508	0	0	706	0	0	706	0	0	0	0	0	0	0
Period 6	152	176	117	0	0	385	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	94	264	128	392	0	0	576	811	591	576	811	591	0	0	0	0	0	0
Period 8	110	201	61	0	508	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	392	253	246	0	0	0	408	877	439	408	877	439	0	0	0	0	0	0
Period 10	116	488	199	392	508	385	0	0	0	0	0	0	0	0	0	0	0	0

Table 3 - Ordering Decisions and Transfers for SKU3

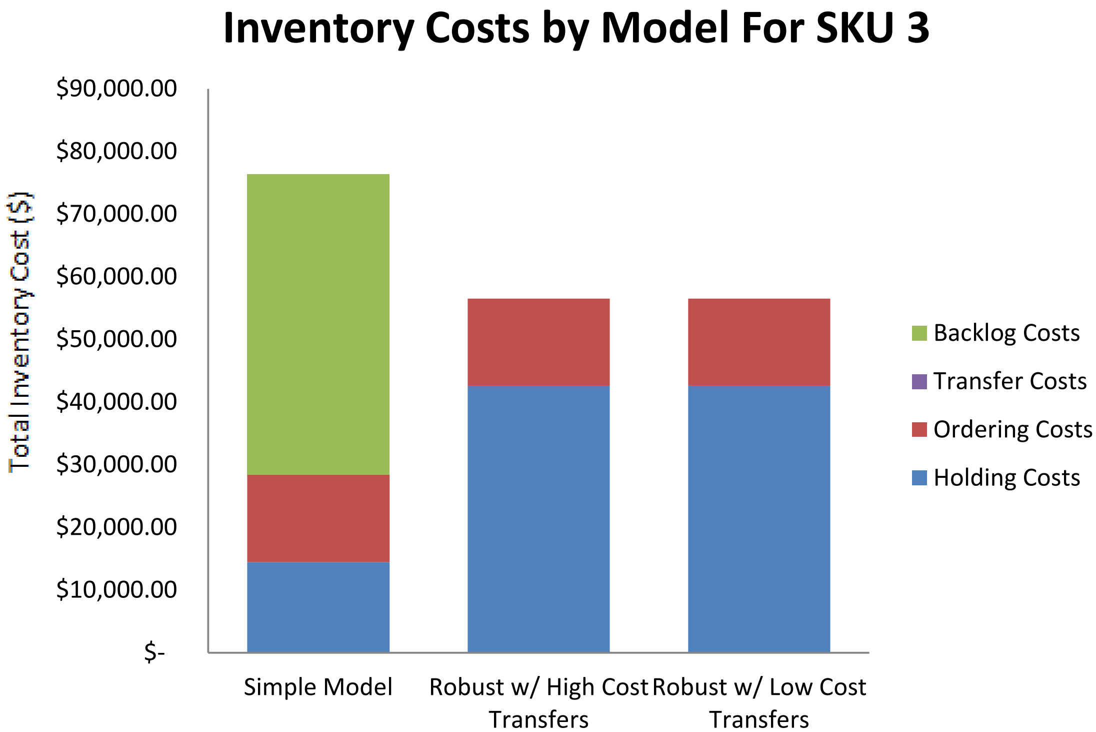


Figure 49 – Inventory Model Total Cost Comparison for SKU 3

Figure 49 above shows the simple model to be the most expensive due to backlog costs. The simple model experienced a single stock out event in a single period. Despite the high costs of backlogging, the simple model achieved a 95% unit fill rate. The high cost of this SKU along with the variability of demand made the transfer option unfavorable for both high and low cost transfers. As expected, the robust model was able to avoid any stock outs due to worst case demand planning.

Figure 50 below shows that all models placed several orders over the 10 periods sampled, as indicated by increases in inventory between periods. As the periods increase, the robust bound (Γ) on total demand variation also increases. The robust model mirrors reality in that the farther in the future you forecast, the more inaccurate the forecast becomes. This characteristic of the robust model is clearly evident by the increasing inventory levels for SKU 3.

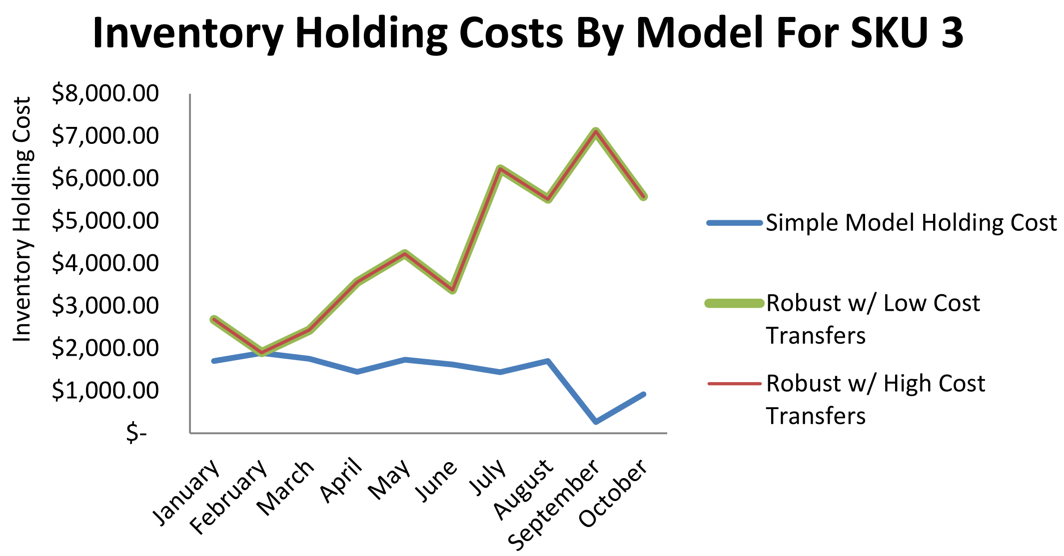


Figure 50 – SKU 3 Holding Costs for Robust vs. Simple Model Comparison

6.3.4 Simple vs. Robust Comparison SKU 4

The fourth SKU we present is a 65' class 1 pole. The purchase price of the item is $1,346, and the monthly average demand from 2011 to 2012 was 11 units per month. This SKU is a Category 'A' item based on the classifications presented at the beginning of this chapter.

Simple Model outputs used for the comparison are:

- Reorder points for CDC1, CDC2, and CDC3 were 9, 31, and 5 respectively.
- The EOQ values for each CDC were 22, 27, and 13 respectively

Robust Model Inputs are:

	Unit Cost	Holding Cost	Backlog Cost	Low Transfer Cost	High Transfer Cost	Fixed Order Cost
CDC1	$ 1,346.00	$ 7.98	$ 1,452.80	$ 15.96	$ 336.50	$ 1,070
CDC2	$ 1,346.00	$ 7.98	$ 1,452.80	$ 15.96	$ 336.50	$ 1,070
CDC3	$ 1,346.00	$ 7.98	$ 1,452.80	$ 15.96	$ 336.50	$ 1,070

The resulting ordering and transferring decisions are presented in Table 4 below:

	Demand			Simple Model Orders			Low Transfer Cost Robust Model Orders			High Transfer Cost Robust Model Orders			Low Transfer Cost Robust Model Transfers			High Transfer Cost Robust Model Transfers		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	0	0	22	27	13	89	0	0	40	35	38	-51	31	20	0	0	0
Period 2	0	1	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	4	11	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	1	0	0	0	0	0	0	0	0	0	-3	0	3	0	0	0
Period 6	4	4	2	0	0	0	75	0	0	0	0	0	-42	27	15	0	0	0
Period 7	11	5	0	0	0	0	0	0	0	28	22	0	0	0	0	0	0	0
Period 8	0	0	2	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	0	5	1	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	0	3	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4 - Ordering Decisions and Transfers for SKU4

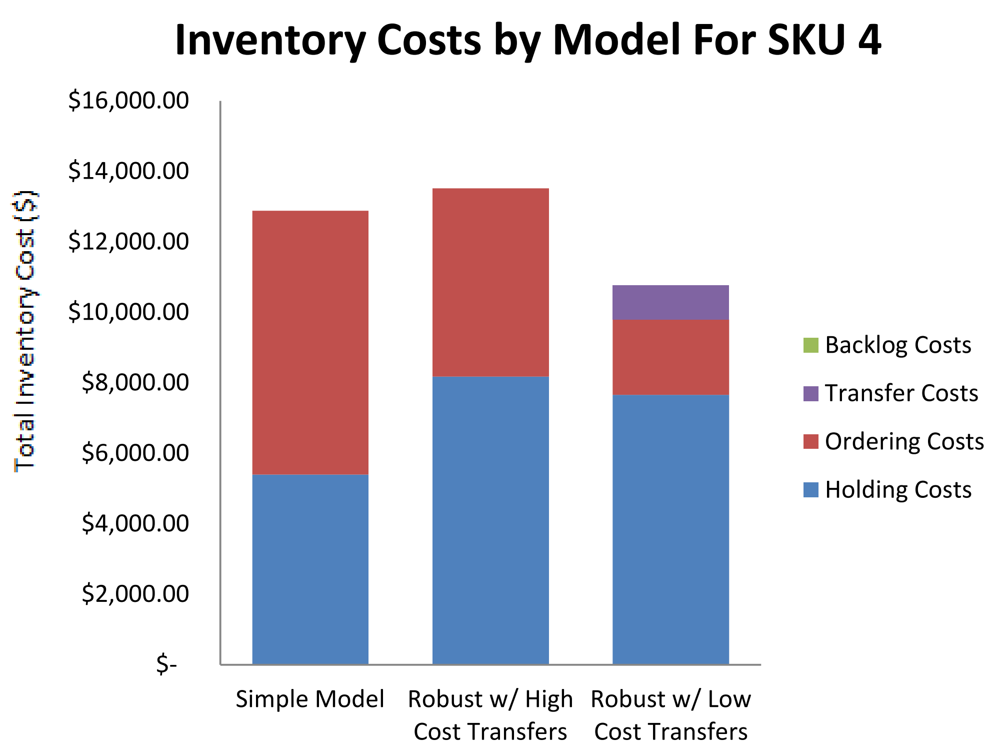


Figure 51 – Inventory Model Total Cost Comparison for SKU 4

Figure 51 above shows a close balance between the expected total costs for all three models. The simple model placed a total of 7 orders compared to the 5 placed by the high cost transfer robust model. Once again, the robust model with low transfer costs favored a single entry point into the network for materials ordered. The high cost transfer robust model ordered independently for each CDC, mimicking the simple model.

Figure 52 below shows a much closer holding costs balance than we saw with the previous three SKUs. The robust model with low transshipment costs increased stock in June, prior to an increase in the standard deviation of demand in Q3 and Q4 of the model. The standard deviation of demand for the second largest CDC tripled between Q2 and Q3. The behavior of the low cost transfer model mirrored that of SKU 2 in Section 6.3.2. An interesting thing to note is that despite different approaches to fulfilling demand given different assumptions of uncertainty, all three models finished the 10th period with similar inventory levels by location.

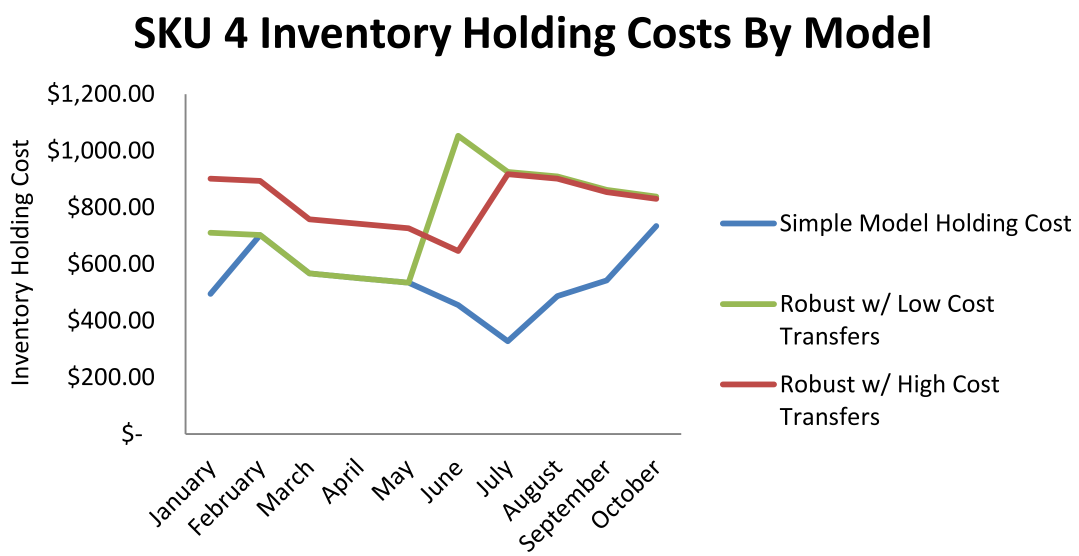


Figure 52 – SKU 4 Holding Costs for Robust vs. Simple Model Comparison

6.3.5 Simple vs. Robust Comparison SKU 5

The final SKU we present is a generic clamp. The purchase price of the item is $5.30, and the monthly average demand from 2011 to 2012 was 1,216 units per month. This SKU is a Category ‘C’ item based on the classifications presented at the beginning of this chapter.

Simple Model outputs used for the comparison are:

- Reorder points for CDC1, CDC2, and CDC3 were 323, 1946, and 289 respectively.
- The EOQ values for each CDC were 915, 4,939, and 159 respectively

Robust Model Inputs are:

	Unit Cost	Holding Cost	Backlog Cost	Low Transfer Cost	High Transfer Cost	Fixed Order Cost
CDC1	$ 5.30	$ 0.03	$ 5.64	$ 0.06	$ 1.31	$ 1,070
CDC2	$ 5.30	$ 0.03	$ 5.64	$ 0.06	$ 1.31	$ 1,070
CDC3	$ 5.30	$ 0.03	$ 5.64	$ 0.06	$ 1.31	$ 1,070

The resulting ordering and transferring decisions are presented in Table 5 below:

	Demand			Simple Model Orders			Low Transfer Cost Robust Model Orders			High Transfer Cost Robust Model Orders			Low Transfer Cost Robust Model Transfers			High Transfer Cost Robust Model Transfers		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	14	236	0	915	4939	159	0	9818	0	1799	8618	1750	175	-200	25	0	0	0
Period 2	183	384	0	0	0	159	0	0	0	0	0	0	157	-200	43	0	0	0
Period 3	89	384	15	0	0	0	0	0	0	0	0	0	154	-200	46	0	0	0
Period 4	0	118	0	0	0	0	0	0	0	0	0	0	140	-200	60	0	0	0
Period 5	59	487	0	0	0	0	0	0	0	0	0	0	100	-200	100	0	0	0
Period 6	29	325	0	0	0	0	0	0	0	0	0	0	198	-200	2	0	0	0
Period 7	35	207	0	0	0	0	0	0	2275	0	0	0	200	0	-200	0	0	0
Period 8	0	502	0	0	0	0	0	0	0	0	0	0	200	0	-200	0	0	0
Period 9	0	546	0	0	0	0	0	0	0	0	0	0	200	0	-200	0	0	0
Period 10	230	929	87	0	4939	0	0	0	0	0	0	0	200	0	-200	0	0	0

Table 5 - Ordering Decisions and Transfers for SKU5

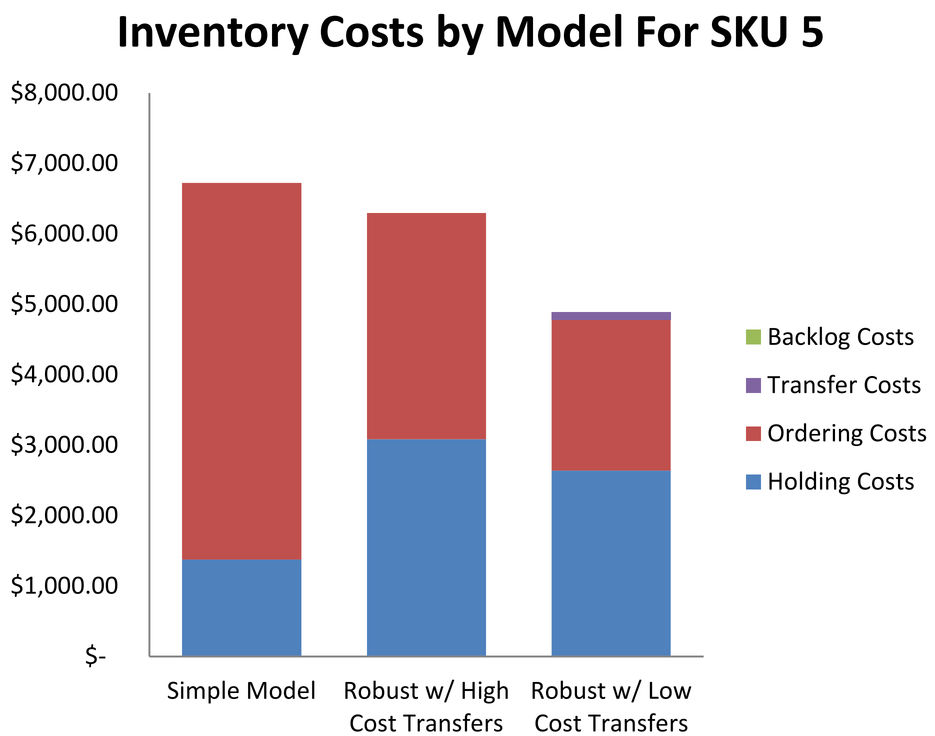


Figure 53 – Inventory Model Total Cost Comparison for SKU 5

Figure 53 above shows a total cost pattern similar to SKU 1 from Section 6.3.1. The simple model showed much higher ordering costs due to placing a total of 5 orders compared to 3 for the high cost transfer model, and 2 for the low cost transfer model.

Figure 54 below shows a holding cost pattern similar to SKU 3, except ending holding costs for all three models were very close at the end of the 10th period. This is coincidental, and not due to any specific characteristics of this SKU. Increased variability in Q3 and Q4 of the model caused an increase in the holding costs associated with the low transfer cost robust model. When transfer costs were high, the model determined that it was more efficient to hold extra inventory in favor of minimizing fixed ordering costs.

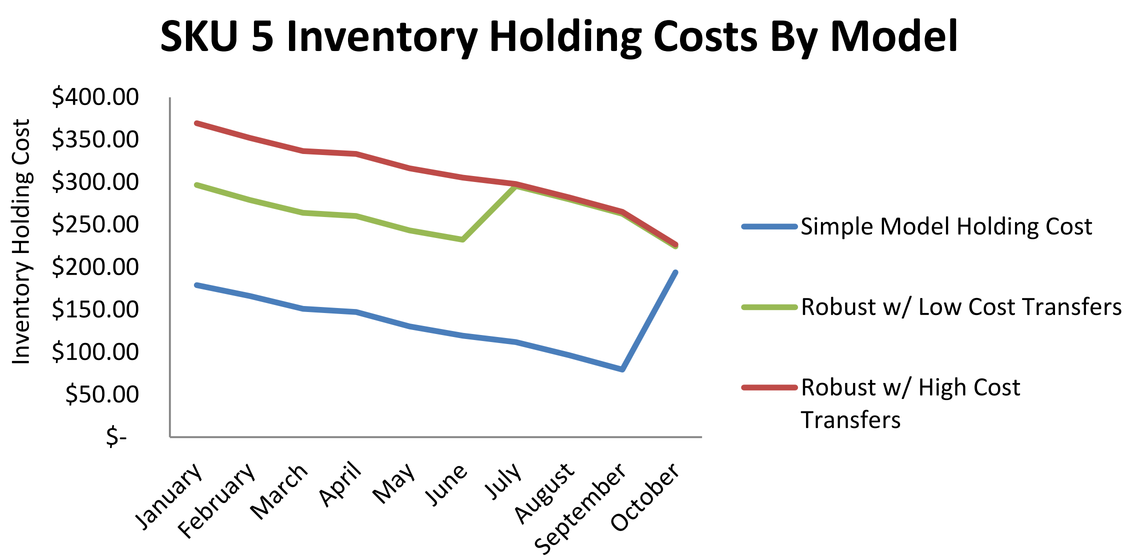


Figure 54 – SKU 5 Holding Costs for Robust vs. Simple Model Comparison

6.3.6 Inventory Model Comparison Summary

Comparing the models has revealed that a robust approach may very likely be a favorable approach over a simple (s,Q) policy in terms of supply chain performance and responsiveness in the short run. In 60% of the examples we presented, both robust models outperformed the simple model in terms of total cost. The robust models favored holding inventory for unfavorable demand fluctuation, which enabled them to avoid stocking out in any of the scenarios we tested. The total costs of the robust model were comparative to the simple (s,Q) model in all but the second example presented.

The robust model has the advantage of varying demand levels during different periods which simulates the seasonality observed in the construction industry well. If space is not a concerning factor, the robust approach seems to be an appropriate model to use given this limited short run example. In order to draw statistically significant conclusions, much larger samples would need to be compared. Our intent from developing these models was to indicate whether or not they would both be worth analyzing as realistic options for Tracks Energy going forward, and based on our analysis they are. One potential outcome would be to use a robust type model for important Category 'A' SKUs when entering a season with an expected increase in storm activity.

6.3.7 Model Sensitivity Analysis for Fixed Ordering and Holding Costs

In this section we will present the model results by again applying a demand string of actual 2012 volume; however we will vary either the holding or fixed ordering costs while holding all other inputs constant. At the end of this section, we will present a sensitivity analysis of the uncertainty level (Γ) for the robust models.

We present a sensitivity analysis of fixed ordering cost for each model using SKU 1 introduced in Section 6.3.1. Table 6 below shows a pattern of decreasing ordering frequencies as the fixed cost of ordering increases. The EOQ order values for CDC1 and CDC3 reach their maximum order quantity of 8 and 9 units respectively because those were the total demand quantities at those CDCs in 2011. Without a cap on EOQ values, the EOQ order quantity would have continued increasing for all CDCs.

	Demand			Simple Model Orders $100 Fixed Cost			Simple Model Orders $500 Fixed Cost			Simple Model Orders $1070 Fixed Cost			Simple Model Orders $1500 Fixed Cost		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	8	29	9	8	52	9	8	52	9	8	52	9
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	9	0	0	9	0	0	9	0	0	9
Period 9	1	12	3	8	0	0	8	0	0	8	0	0	0	0	0
Period 10	0	0	0	0	29	0	0	0	0	0	0	0	0	0	0

Table 6 – Simple Model Decisions with Increasing Fixed Ordering Costs

Figure 55 below shows the simple model total costs with varying levels of fixed ordering costs for SKU1. Since the inventory level for each CDC in the first period is 0, each model is forced to order in the first period for each CDC. This has a significant impact to the total ordering costs for each level of fixed costs. Figure 55 also shows holding costs increasing as ordering costs increase.

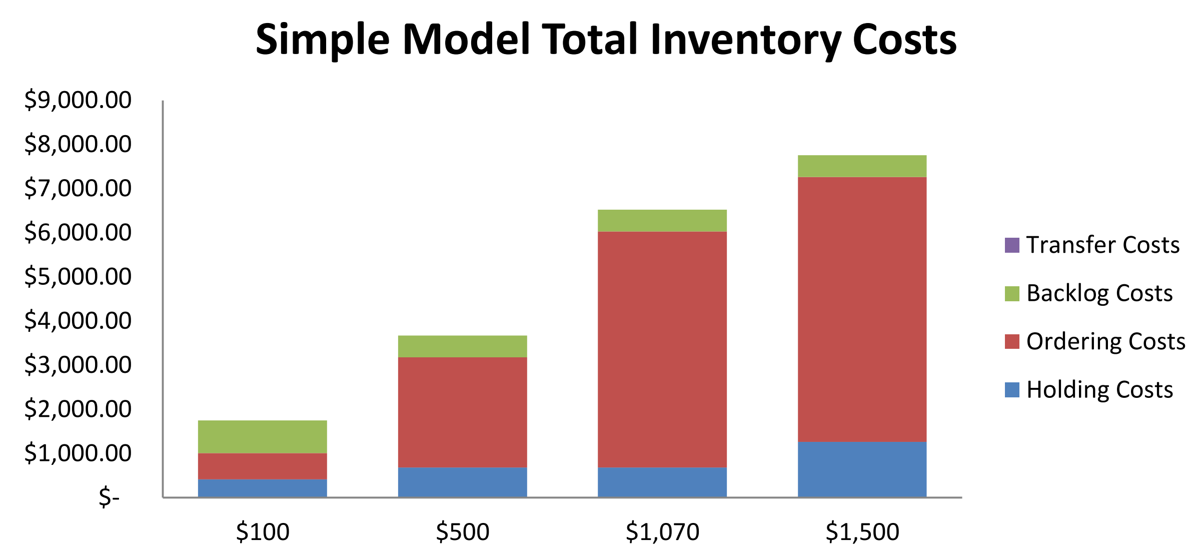


Figure 55 – Total Simple Model Costs for Four Different Levels of Fixed Ordering Costs

Figure 56 below shows the inventory levels by month for each of the four fixed ordering cost levels. This graph clearly shows that the simple model favors holding more inventory as fixed ordering costs increase. This result is intuitive since the simple model is designed to balance holding and fixed costs over an infinite horizon. The orders placed when the ordering costs are $500 are identical to the orders placed when ordering costs are $1070, and thus these lines overlap completely in Figure 56.

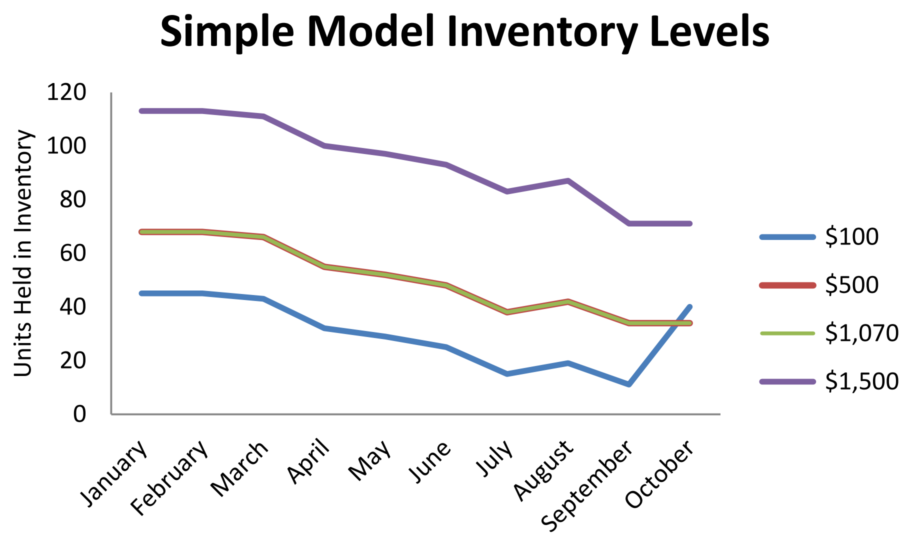


Figure 56 –Simple Model Inventory Levels by Month for Varying Fixed Ordering Costs

The total cost of the robust model with low cost transfers has a shape similar to the simple model (see Figure 57). As the fixed cost of ordering increases, the model places fewer orders, and holds more inventory over longer periods of time.

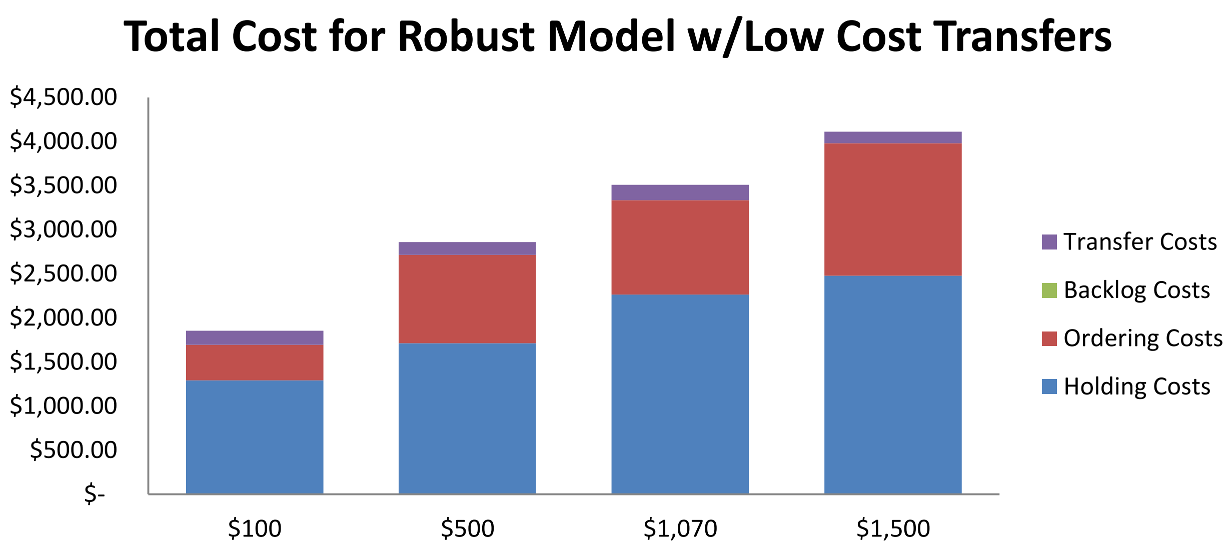


Figure 57 – Total Inventory Costs for the Robust Model w/Low Cost Transfers

Table 6 below shows the same pattern of decreasing orders given increasing fixed ordering costs. As fixed ordering costs increase, the model transfers the same quantities of materials between CDCs, but the number of transfers also decreases. When an order is placed, the low cost transfer robust model transfers all of the units between buildings. The result is a decrease in transfer frequency when the ordering frequency decreases.

	Demand			Low Transfer Cost Robust Model Orders $100 Fixed Cost			Low Transfer Cost Robust Model Orders $500 Fixed Cost			Low Transfer Cost Robust Model Orders $1070 Fixed Cost			Low Transfer Cost Robust Model Orders $1500 Fixed Cost		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	0	31	0	0	88	0	0	212	0	0	212	0
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	57	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	54	0	0	124	0	0	0	0	0	0	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	70	0	0	0	0	0	0	0	0	0	0
Period 9	1	12	3	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Low Transfer Cost Robust Model Transfers $100 Fixed Cost			Low Transfer Cost Robust Model Transfers $500 Fixed Cost			Low Transfer Cost Robust Model Transfers $1070 Fixed Cost			Low Transfer Cost Robust Model Transfers $1500 Fixed Cost		
CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
6	-18	12	12	-16	4	23	-71	48	39	-87	48
0	0	0	0	-16	16	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
6	-15	9	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
10	-21	11	26	-53	27	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
5	-21	16	0	0	0	5	-5	0	0	0	0
11	-11	0	0	0	0	11	-11	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0

Table 7 – Robust Model with Low Cost Transfer Decisions with Increasing Fixed Ordering Costs

Figure 58 below clearly shows the robust model with low cost transfers carrying less inventory when the fixed costs are low. The recommended inventory policy is drastically different depending if high or low ordering costs are chosen. It will be important to get a reasonable estimate of the true fixed ordering costs in order for this model to suggest an optimal inventory policy given worst case demand planning.

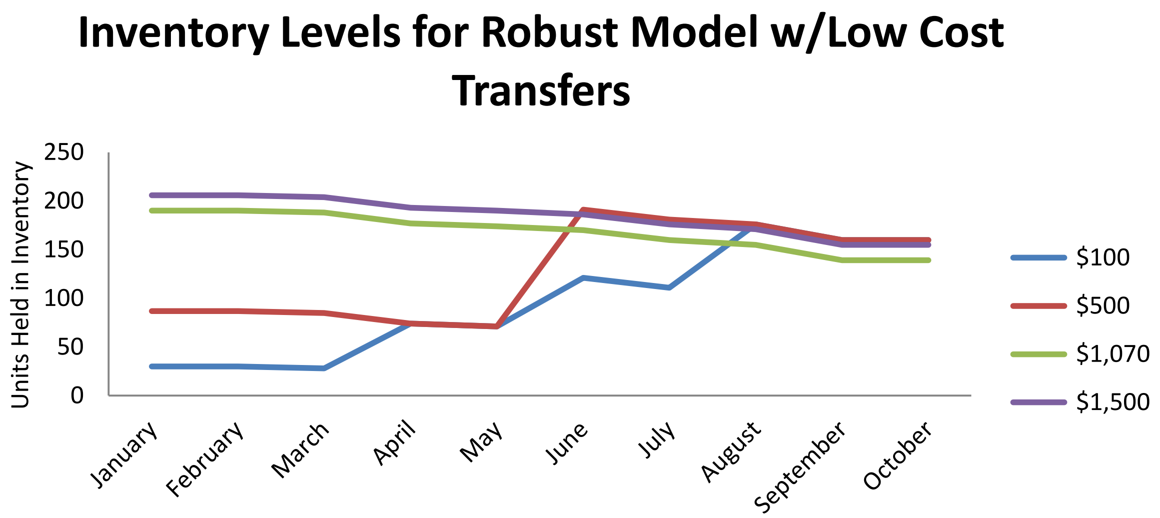


Figure 58 –Inventory Levels for the Robust Model w/Low Cost Transfers

The total costs given increasing fixed ordering costs for the robust model with high cost transfers mimics the results already shown (see Figure 59 below). The most significant difference is that the model has identical holding costs for fixed ordering values of $500, $1,070 and $1500. In each of these scenarios, the model places one order for each CDC in the first period, and then lets inventory deplete in the remaining periods.

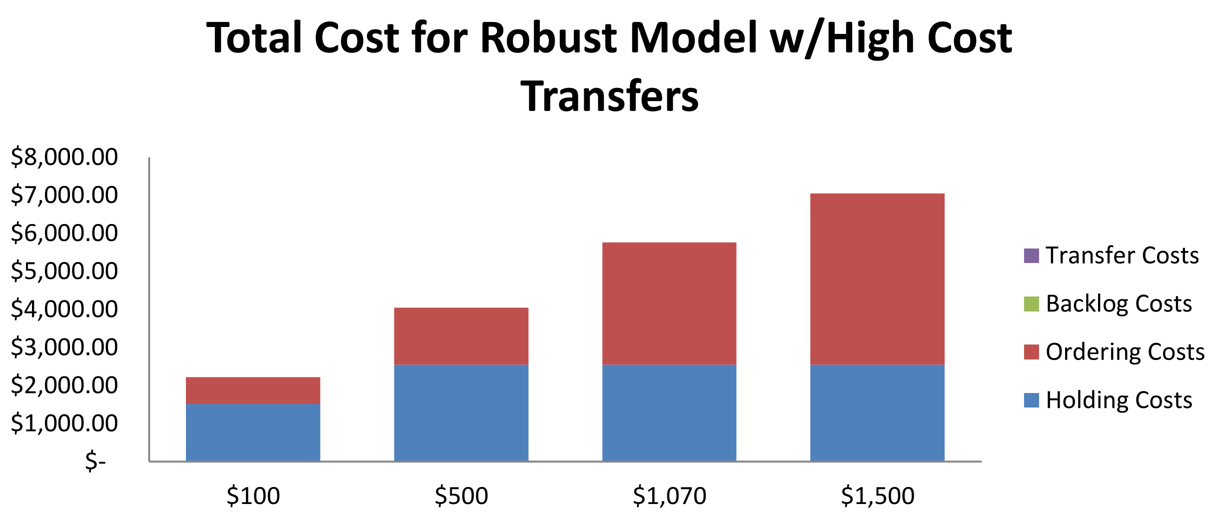


Figure 59 – Total Inventory Costs for the Robust Model w/High Cost Transfers

Table 8 below shows ordering pattern seen in the previous two models carries over when the transfer costs are increased. The high transfer cost model did not include any transfers for any of the fixed ordering cost levels, and thus ordered for each CDC independently. Notice that once the fixed ordering costs increased to $500, all of the material needed for all 10 periods was ordered in the first period.

	Demand			High Transfer Cost Robust Model Orders $100 Fixed Cost			High Transfer Cost Robust Model Orders $500 Fixed Cost			High Transfer Cost Robust Model Orders $1070 Fixed Cost			High Transfer Cost Robust Model Orders $1500 Fixed Cost		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	16	13	25	39	125	48	39	125	48	39	125	48
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	61	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	3	3	4	23	51	23	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	1	12	3	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8 - Robust Model with High Cost Transfer Decisions with Increasing Fixed Ordering Costs

Figure 60 below shows that this model also favors lower inventory levels for low fixed ordering costs. In this example, fixed ordering cost of $500 or more yielded the same recommended inventory policy, and thus all three fixed ordering cost levels had identical holding costs.

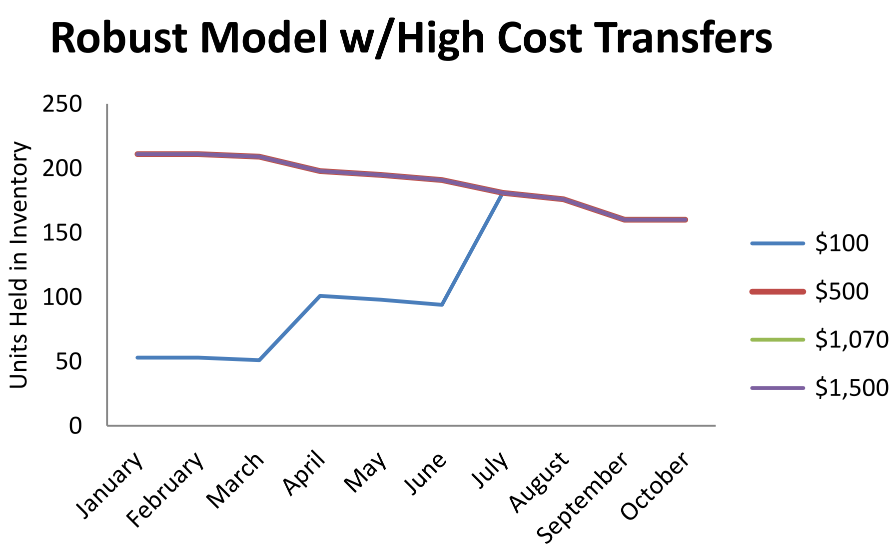


Figure 60 - Inventory Levels for the Robust Model w/High Cost Transfers

All three of the models we have presented in this thesis conform to the well-known intuition of a tradeoff between holding and fixed ordering costs. As fixed ordering costs increase, it becomes more expensive to place frequent orders, and thus inventory levels should increase to offset the increase in fixed ordering costs. While fixed ordering costs are usually hard to calculate in the real world, this analysis shows that randomly selecting an arbitrary value can have significant cost implications when it comes to optimizing inventory ordering policies.

Now that we have an understanding of how the models behave with various levels of fixed ordering costs, we turn our attention to how they behave with varying levels of holding costs. In the following scenarios we use the same fixed holding cost that we used in section 6.3, and we hold all other input variables constant. The total cost charts associated with increasing holding costs showed the same pattern we saw by increasing fixed ordering costs. As inventory holding costs increase, the total cost of the models increase. We do not repeat the total cost results in this section, but rather focus our attention on inventory levels.

Table 9 below shows the orders placed by the simple model with increasing holding costs. What we expected to see was that smaller orders would be placed more frequently when holding costs increased. The data below does not support our hypothesis because the limitations on the max value for EOQ (equal to the total demand observed in 2011) set the EOQ values artificially low. In fact, we did not see any variation until the holding costs increased to 25%, when the order quantity for CDC2 decreased by a single unit.

	Demand			Simple Model Orders 5% Holding Cost			Simple Model Orders 7.35% Holding Cost			Simple Model Orders 15% Holding Cost			Simple Model Orders 25% Holding Cost Cost		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	8	52	9	8	52	9	8	52	9	8	51	9
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	9	0	0	9	0	0	9	0	0	9
Period 9	1	12	3	8	0	0	8	0	0	8	0	0	8	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 9 - Simple Model Decisions with Increasing Holding Costs

Figure 61 below shows lower inventory levels corresponding with increases in holding costs for the simple model without limiting the EOQ value to a maximum of the 2011 total demand. Increasing holding costs in the simple model result in smaller EOQ values, and smaller EOQ values result in smaller order quantities placed more frequently.

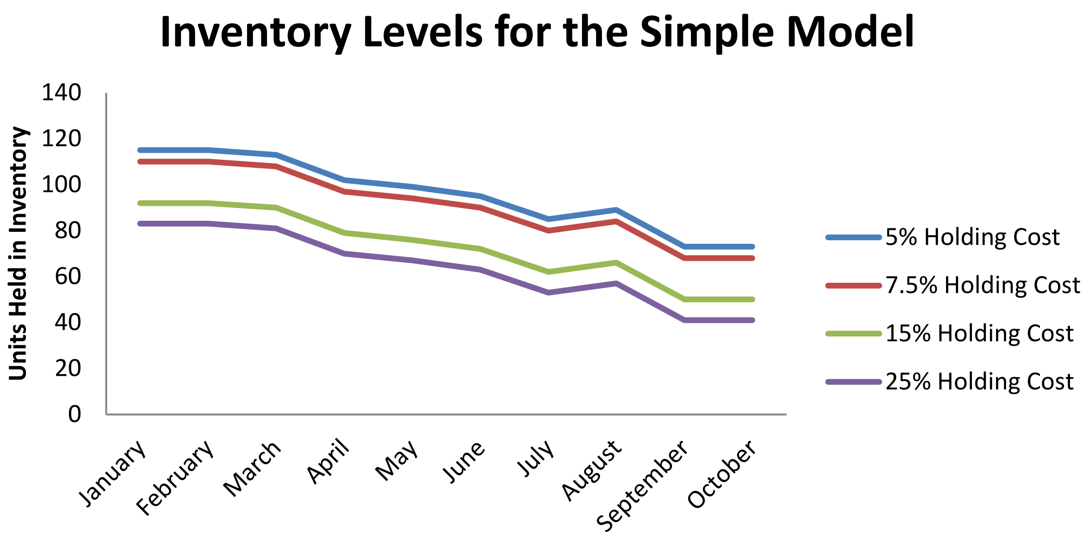


Figure 61 - Simple Model Inventory Levels by Month for Varying Holding Costs

Figure 62 below shows a similar result for the robust model with low cost transfers. When holding costs are low, the model places a single order. However, when holding costs increase, the model places one additional order. This result coincides with the behavior of the simple model. One important thing to note is that the robust model orders less total material when the inventory holding cost increases to 25%. Since the robust model is not following a (s,Q) inventory policy, it is able to balance the risk of stocking out against the cost of carrying extra inventory.

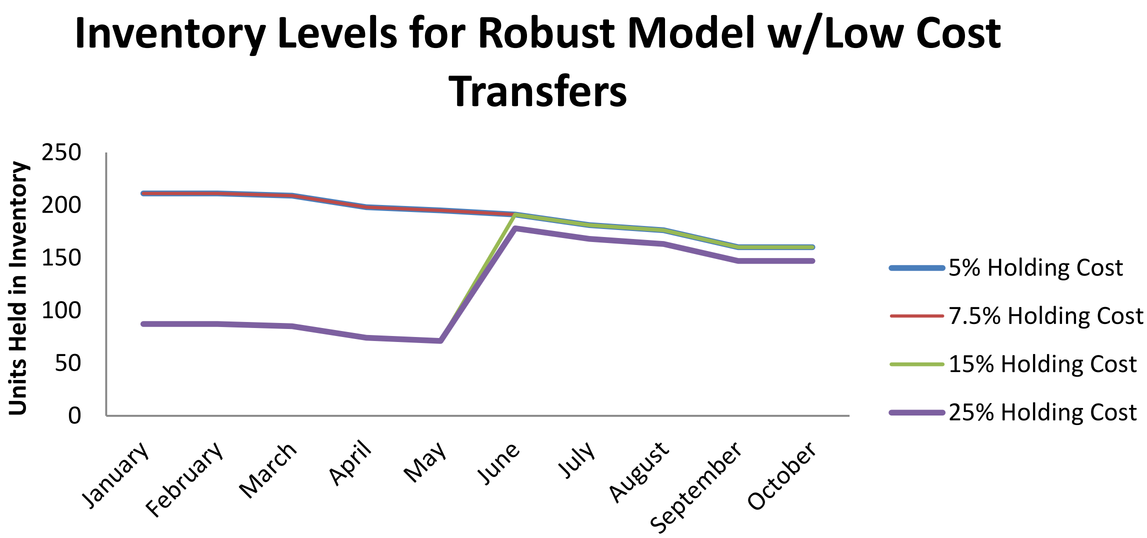


Figure 62 - Inventory Levels for the Robust Model w/Low Cost Transfers

The ordering decisions resulting in the holding costs shown in Figure 62 are shown in Table 10 below. As holding costs increased, the low transfer cost robust model placed two orders over the time horizon rather than one. This pattern supports our hypothesis that ordering quantities should decrease and the number of orders placed should increase as holding costs increase.

	Demand			Low Transfer Cost Robust Model Orders 5% Holding Cost			Low Transfer Cost Robust Model Orders 7.35% Holding Cost			Low Transfer Cost Robust Model Orders 15% Holding Cost			Low Transfer Cost Robust Model Orders 25% Holding Cost		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	0	212	0	0	212	0	0	88	0	0	88	0
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	124	0	0	111	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	1	12	3	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Low Transfer Cost Robust Model Transfers 5% Holding Cost			Low Transfer Cost Robust Model Transfers 7.35% Holding Cost			Low Transfer Cost Robust Model Transfers 15% Holding Cost			Low Transfer Cost Robust Model Transfers 25% Holding Cost		
CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
23	-71	48	23	-71	48	12	-28	16	12	-32	20
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	-4	4	0	0	0
0	0	0	0	0	0	26	-53	27	20	-41	21
0	0	0	0	0	0	0	0	0	0	0	0
5	-5	0	5	-5	0	0	0	0	0	0	0
11	-11	0	11	-11	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0

Table 10 - Robust Model with Low Cost Transfer Decisions with Increasing Holding Costs

Figure 63 below continues the theme that we have seen with the other two models. In this example, when the ordering costs are below 15%, a single order is placed for each warehouse in the first period. When the holding costs increase to 15%, one additional order is placed, and when holding costs increase to 25%, two additional orders are placed. Since the high cost transfer model orders for each building independently, higher inventory levels are seen across the system. The cost of holding this extra inventory that is not transferred results in lower total order quantities for both the 15% and the 25% holding cost scenarios.

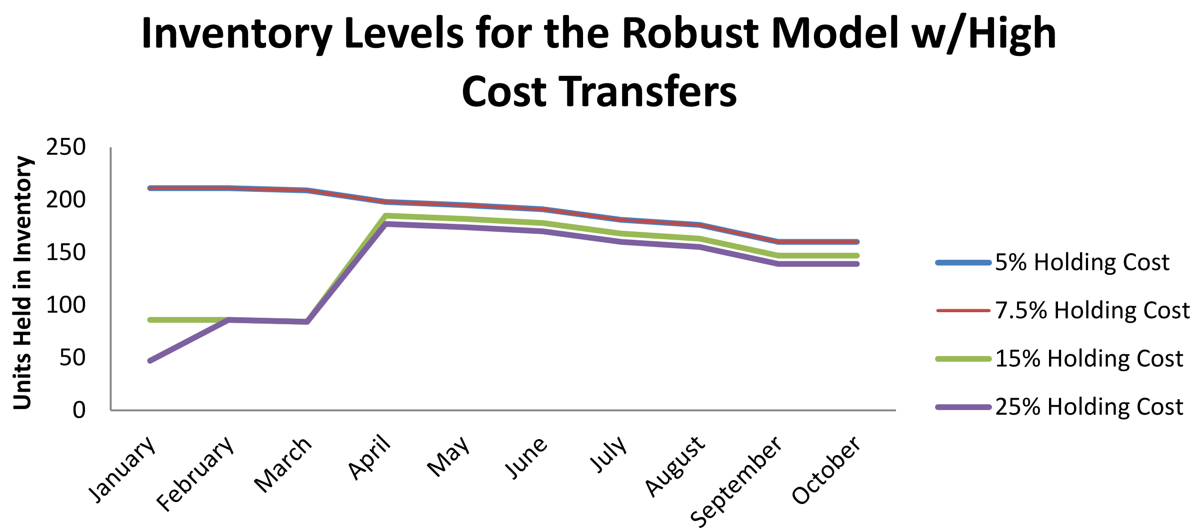


Figure 63 - Inventory Levels for the Robust Model w/High Cost Transfers

The ordering and transferring decisions resulting in the inventory positions shown in Figure 63 are shown below in Table 11. One interesting outcome of this exercise is that the high cost transfer model favors transferring units as holding costs increase, but it did not as fixed ordering costs increased. The ordering decisions clearly show that it is more favorable to place orders more frequently as holding costs increase, and fixed order costs are held constant.

	Demand			High Transfer Cost Robust Model Orders 5% Holding Cost			High Transfer Cost Robust Model Orders 7.35% Holding Cost			High Transfer Cost Robust Model Orders 15% Holding Cost			High Transfer Cost Robust Model Orders 25% Holding Cost		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	39	125	48	39	125	48	37	0	50	0	0	48
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	39	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	0	0	0	0	0	0	112	0	0	104	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	1	12	3	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

High Transfer Cost Robust Model Transfers 5% Holding Cost			High Transfer Cost Robust Model Transfers 7.35% Holding Cost			High Transfer Cost Robust Model Transfers 15% Holding Cost			High Transfer Cost Robust Model Transfers 25% Holding Cost		
CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
0	0	0	0	0	0	0	4	-4	2	4	-6
0	0	0	0	0	0	0	4	-4	-8	8	0
0	0	0	0	0	0	-4	4	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0

Table 11 - Robust Model with High Cost Transfer Decisions with Increasing Holding Costs

In this section we looked at each model's sensitivity to holding costs and fixed ordering costs for a single SKU. All of the models demonstrated the same general characteristics. As fixed ordering costs increase, it is more economical to place fewer orders of larger quantities. Conversely, as holding costs increase, it is more economical to place smaller orders more frequently. Understanding the actual relationship between fixed ordering costs and holding costs can have significant cost implications for the optimal ordering policy. While it is typically difficult to understand the exact ordering and holding costs, this exercise shows that it is worth investing time and effort to estimate these values.

6.3.8 Model Sensitivity Analysis for the Robust Budget of Uncertainty (Γ)

In addition to average demand and standard deviation in each period, the robust model includes a parameter regarding the total budget of uncertainty (Γ). As the level of uncertainty approaches 0, the robust model optimizes the known average demand with standard deviation values for each CDC in each period. As the level of uncertainty increases, the variability of demand expectations is allowed to increase. In this section we will review four different levels of uncertainty for SKU1 to analyze their impact on the inventory policies suggested by the robust model. The other inputs into the robust model will be identical to those used to compare model results in Section 6.3.1.

In Section 6.3 we chose a Γ for each period equal to $\frac{1}{4}\sqrt{n}$, where n was equal to the time period. In Table 12 below, we present the ordering and transferring decisions given increasing levels of uncertainty for the robust model with low transfer costs. As the level of uncertainty increases, the total quantity of material ordered increases to protect against larger unfavorable demand tolerances used by the model.

	Demand			Low Transfer Cost Robust Model Orders 0 Budget of Uncertainty			Low Transfer Cost Robust Model Orders 1/4th *sqrt(n) Budget of Uncertainty			Low Transfer Cost Robust Model Orders 1/2 *sqrt(n) Budget of Uncertainty			Low Transfer Cost Robust Model Orders 1 *sqrt(n) Budget of Uncertainty		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	0	196	0	0	212	0	0	236	0	0	261	0
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	1	12	3	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Low Transfer Cost Robust Model Transfers 0 Budget of Uncertainty			Low Transfer Cost Robust Model Transfers 1/4th *sqrt(n) Budget of Uncertainty			Low Transfer Cost Robust Model Transfers 1/2 *sqrt(n) Budget of Uncertainty			Low Transfer Cost Robust Model Transfers 1 *sqrt(n) Budget of Uncertainty		
CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
4	-8	4	2	-50	48	1	-36	35	48	-52	4
0	-8	8	4	-4	0	3	-21	18	0	-53	53
21	-21	0	0	0	0	0	0	0	0	0	0
0	-12	12	6	-6	0	7	-7	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	20	-20	0	28	-28	0	0	0	0
0	-5	5	0	0	0	0	0	0	0	0	0
0	-5	5	0	0	0	0	0	0	0	0	0
11	-22	11	0	0	0	0	0	0	0	0	0
0	0	0	6	-6	0	0	0	0	0	0	0

Table 12 - Robust Model with Low Cost Transfer Decisions with Increasing Budgets of Uncertainty

In Figure 64 below, we can see that increasing the uncertainty level increases the total expected cost of the optimized inventory policies. The only variation caused by increasing uncertainty was the order quantities in each period. As the uncertainty factor increased, more inventory was ordered to accommodate the increase in worst case demand values.

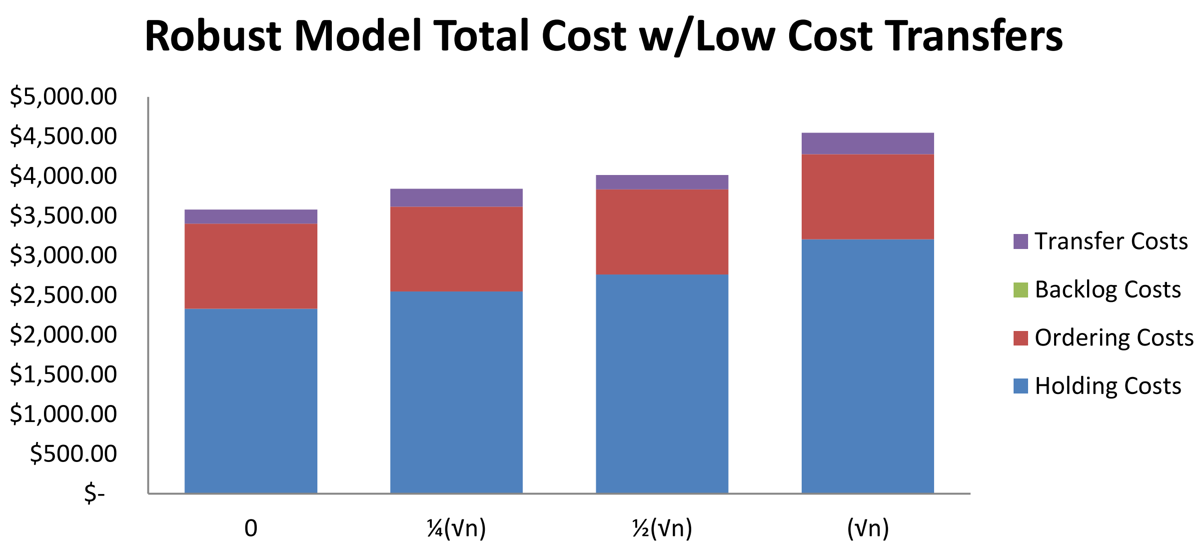


Figure 64 – Total Inventory Cost for the Robust Model with Low Transfer Costs and Varying Levels of Uncertainty

Figure 65 below shows that the inventory stocking decisions were consistent in spite of increasing uncertainty levels. By increasing the uncertainty factor from 0 to the $\sqrt{n}$, the model increased inventory levels by 33%.

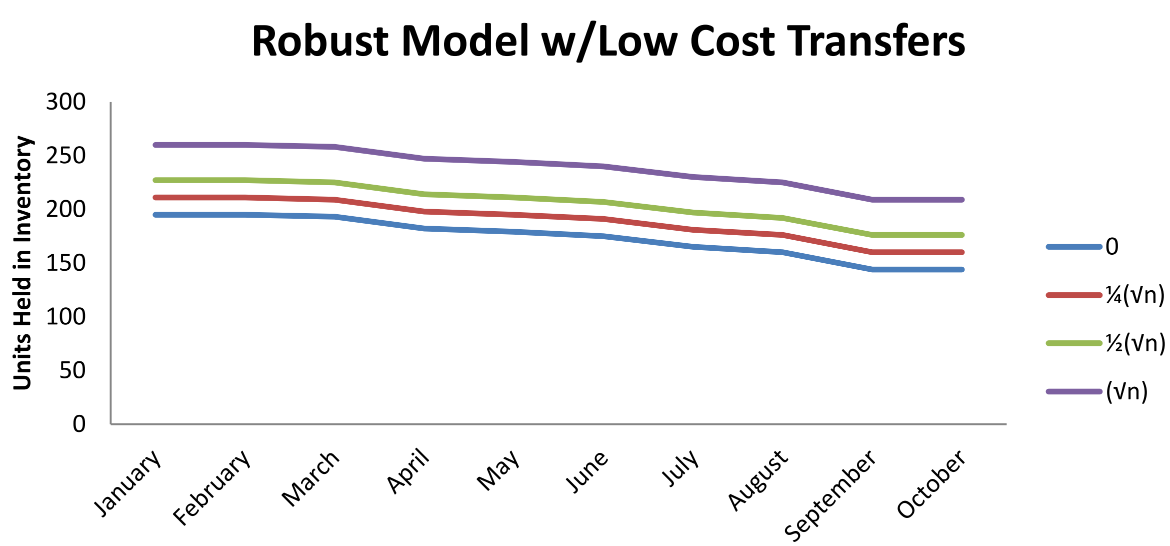


Figure 65 - Inventory Levels for the Robust Model w/Low Cost Transfers and Increasing Uncertainty

When considering high transfer costs, increasing uncertainty only increased the quantity ordered. The increases in values were identical to the quantities seen with low transfer costs. Table 13 below shows increasing order quantities as the budgeted level of uncertainty increases. With high transfer costs, the robust model does not transfer any units. Increasing budgets of uncertainty did not have any impact on the decision to transfer material.

	Demand			High Transfer Cost Robust Model Orders 0 Budget of Uncertainty			High Transfer Cost Robust Model Orders 1/4th *sqrt(n) Budget of Uncertainty			High Transfer Cost Robust Model Orders 1/2 *sqrt(n) Budget of Uncertainty			High Transfer Cost Robust Model Orders 1 *sqrt(n) Budget of Uncertainty		
	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3	CDC1	CDC2	CDC3
Period 1	0	1	0	36	115	45	36	115	45	42	135	51	48	155	57
Period 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Period 3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 4	0	9	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 5	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 6	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0
Period 7	3	3	4	0	0	0	0	0	0	0	0	0	0	0	0
Period 8	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
Period 9	1	12	3	0	0	0	0	0	0	0	0	0	0	0	0
Period 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 13 - Robust Model with High Cost Transfer Decisions with Increasing Budgets of Uncertainty

Figure 66 below, shows that the only effect of increasing uncertainty was an increase in holding costs. The total inventory levels were identical to those shown in Figure 65. The only difference between the two robust models was that the high transfer cost model did not include transfers, and ordered for each building independently.

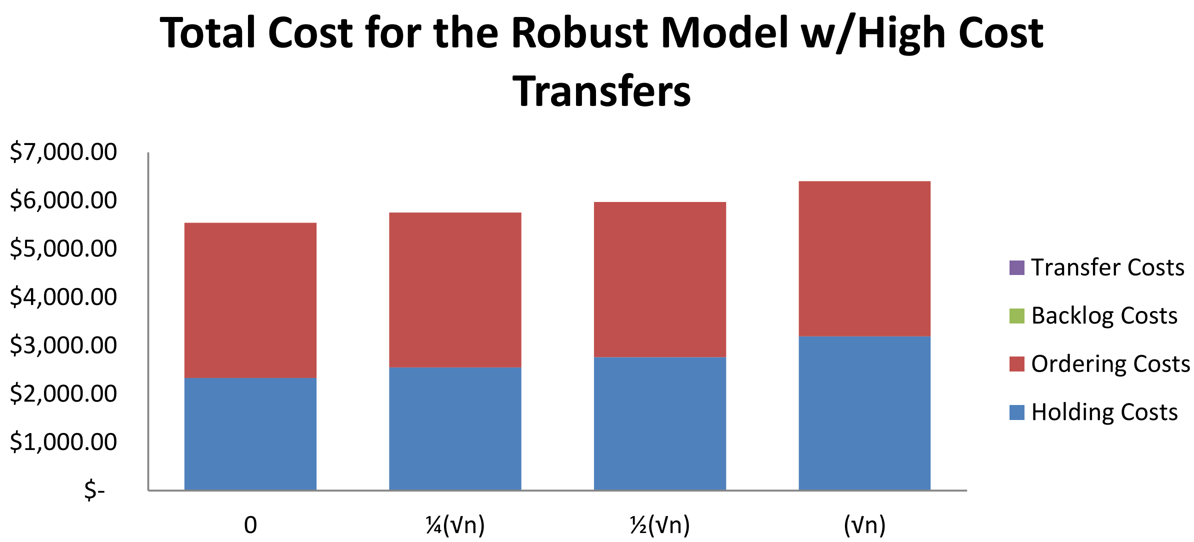


Figure 66 - Total Inventory Cost for the Robust Model with High Transfer Costs and Varying Levels of Uncertainty

In this section we looked at the sensitivity of different levels of uncertainty allowed by the robust model. Increasing the uncertainty level only changed the optimal order quantity to protect against unfavorable demand. The optimal decisions for when to order the material did not change.

6.3.9 Sensitivity Analysis for Simple Model without Normal Demand

The gamma distribution is favored by some inventory modeling researchers, when modeling SKUs with small demand quantities, because demand is forced to be greater than or equal to 0. Fortuin (Fortuin, 1980) showed that normal demand assumptions result in inventory policies that are very close to policies derived from other distributions, such as the gamma distribution. In this section we present the performance of the simple model, the robust model with low cost transfers, and the robust model with high cost transfers, with demand inputs based on the gamma distribution rather than 2012 actual demand.

In order to ensure the gamma distributions we used to generate demand had the properties of the observed 2011 data, we use the 2011 average demand and standard deviation for each fiscal quarter to determine the input parameters of the gamma distribution for each SKU. We did not base our gamma distribution on 2012 data because we only had one data point for the fourth quarter. Using 2011 data allowed us to preserve seasonality trends of the input demand in addition to the expected demand values.

The mean of the gamma distribution is defined by two input parameters (k,Θ). The characteristics of the gamma distribution are defined by Equation 35 and Equation 36 below.

$$Mean = \mathrm{k} * \Theta$$

Equation 35 – Mean Value of the Gamma Distribution

$$Standard\ Deviation = \sqrt{k * \Theta^2}$$

Equation 36 – Standard Deviation of the Gamma Distribution

For each SKU we present in this section, we set the mean and standard deviation of the gamma distribution equal to the mean and standard deviation of the 2011 observed demand for each quarter. An example of this procedure is shown below for SKU1 at CDC1:

- 2011 Q1 Average Demand: 1
- 2011 Q1 Standard Deviation of Demand: 0.98

We set k*Θ = 1 and $\sqrt{k * \theta^2}$ = .98 and solved for the variables k and Θ. The results were:

- k = 0.7184
- Θ = 1.16

We used Microsoft Excel's *gamma.inv* formula with a random number generator to generate demand strings for each CDC, and then we simulated the ordering of material based on the simple model inventory policies.

	2011 Q1		2011 Q2		2011 Q3		2011 Q4	
	k	**Θ**	**k**	**Θ**	**k**	**Θ**	**k**	**Θ**
CDC1	0.72	1.16	2.08	3.61	0.86	5.22	0.69	1.80
CDC2	0.17	1.00	0.36	1.40	0.72	2.32	1.05	1.67
CDC3	0.42	1.60	10.42	0.16	0.73	2.07	1.93	0.90

Table 14 below shows the gamma distribution parameters for SKU1. These parameters were used to create synthetic demand strings for each CDC over the same ten period time horizon that we have shown throughout Chapter 6.

	2011 Q1		2011 Q2		2011 Q3		2011 Q4	
	k	**Θ**	**k**	**Θ**	**k**	**Θ**	**k**	**Θ**
CDC1	0.72	1.16	2.08	3.61	0.86	5.22	0.69	1.80
CDC2	0.17	1.00	0.36	1.40	0.72	2.32	1.05	1.67
CDC3	0.42	1.60	10.42	0.16	0.73	2.07	1.93	0.90

Table 14 – SKU1 Gamma Distribution Parameters for each CDC

Table 15 below shows the original 2012 observed demand for SKU1 in addition to the new demand generated from a gamma distribution.

2012 Observed Demand for SKU1

	CDC1	CDC2	CDC3
January	0	1	0
February	0	0	0
March	0	0	2
April	0	9	2
May	0	1	2
June	1	2	1
July	3	3	4
August	1	2	2
September	1	12	3
October	0	0	0
Total Demand	6	30	16

Gamma Distribution Demand for SKU1

	CDC1	CDC2	CDC3
January	0	0	0
February	0	1	0
March	0	2	0
April	0	13	7
May	0	15	11
June	0	16	10
July	3	5	0
August	1	2	0
September	1	2	1
October	8	0	3
Total Demand	13	56	32

Table 15 – Observed Demand and Gamma Distribution Demand for SKU1

For our analysis of the performance of each model, we started with an initial inventory level of 0 at each CDC, and assumed a lead time of 0 for each order placed. The total inventory costs by model are shown in Figure 67 below.

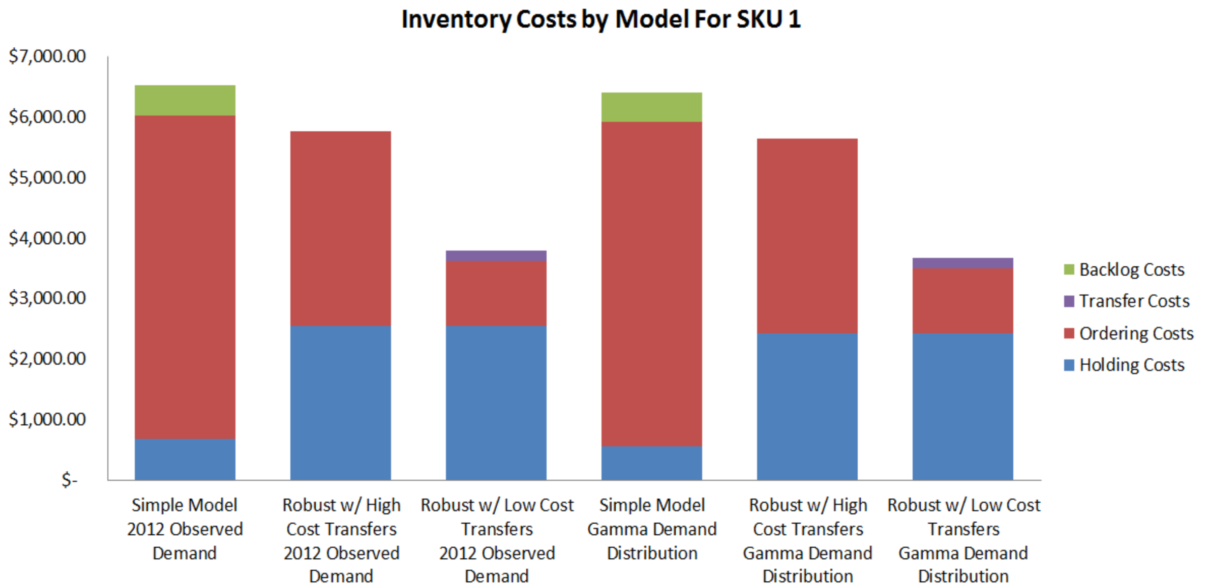


Figure 67 – SKU1 Total Inventory Costs for each Model with 2012 Observed Demand and Gamma Distribution Demand

After simulating the performance of each model by applying the new demand strings to each CDC based on the gamma distribution, we found ordering decisions were identical to the ones observed when actual 2012 demand was used. The only cost differences between the scenarios with actual demand and those with synthetic gamma distribution demand were due to inventory holding costs. Table 16 below shows that the balance between holding and ordering costs between similar models was less than 3% for any of the scenarios.

	Simple Model 2012 Observed Demand	Simple Model Gamma Demand Distribution	Robust w/ Low Cost Transfers 2012 Observed Demand	Robust w/ Low Cost Transfers Gamma Demand Distribution	Robust w/ High Cost Transfers 2012 Observed Demand	Robust w/ High Cost Transfers Gamma Demand Distribution
Holding Costs	10%	9%	67%	66%	44%	43%
Ordering Costs	82%	84%	28%	29%	56%	57%
Backlog Costs	8%	8%	0%	0%	0%	0%
Transfer Costs	0%	0%	5%	5%	0%	0%

Table 16 – SKU1 Inventory Costs by Percentage for Each Simulated Model Scenario

The inventory policies of the robust models are based on the average demand and standard deviation of each quarter, and thus were identical for both the 2012 demand and gamma distribution demand scenarios. The simple model inventory policies resulted in the same number of orders, and the same quantity of units ordered for both the 2012 demand and gamma distribution demand scenarios. For this example SKU, the actual distribution of demand had a minimal effect on the total cost of each scenario.

Table 17 below shows the gamma distribution parameters for SKU2. These parameters were used to create synthetic demand strings for each CDC over the same ten period time horizon that we showed for SKU1.

	2011 Q1		2011 Q2		2011 Q3		2011 Q4	
	k	Θ	k	Θ	k	Θ	k	Θ
CDC1	0.30	2.20	2.67	2.00	0.51	4.92	0.43	19.26
CDC2	0.36	1.40	0.89	2.05	2.88	1.27	3.36	0.82
CDC3	0.72	1.16	0.60	2.80	1.23	0.68	0.75	0.67

Table 17 – SKU2 Gamma Distribution Parameters for each CDC

Table 18 below shows the simulated demand values based on a gamma distributions with the parameters shown in Table 17.

2012 Observed Demand for SKU2

	CDC1	CDC2	CDC3
January	0	0	1
February	0	2	1
March	0	0	0
April	0	9	0
May	2	3	2
June	5	1	1
July	1	4	0
August	7	5	2
September	5	14	2
October	2	17	1
Total Demand	22	55	10

Gamma Distribution Demand for SKU2

	CDC1	CDC2	CDC3
January	0	5	1
February	0	0	2
March	0	5	0
April	4	5	0
May	1	6	2
June	7	2	3
July	1	1	1
August	1	0	0
September	5	0	1
October	4	1	0
Total Demand	23	25	10

Table 18 - Observed Demand and Gamma Distribution Demand for SKU2

The total inventory costs by model are shown in Figure 68 below. The number of orders, and the quantity of SKUs, ordered by the robust models were again identical to the decisions observed with actual 2012 demand. The simple model simulated with gamma distribution demand, however, placed one additional order resulting in an increase in ordering costs. The lower total demand for SKU2 at CDC2 (see Table 18 above) resulted in larger inventory holding costs for the simple and robust models simulated with demand from the gamma distribution.

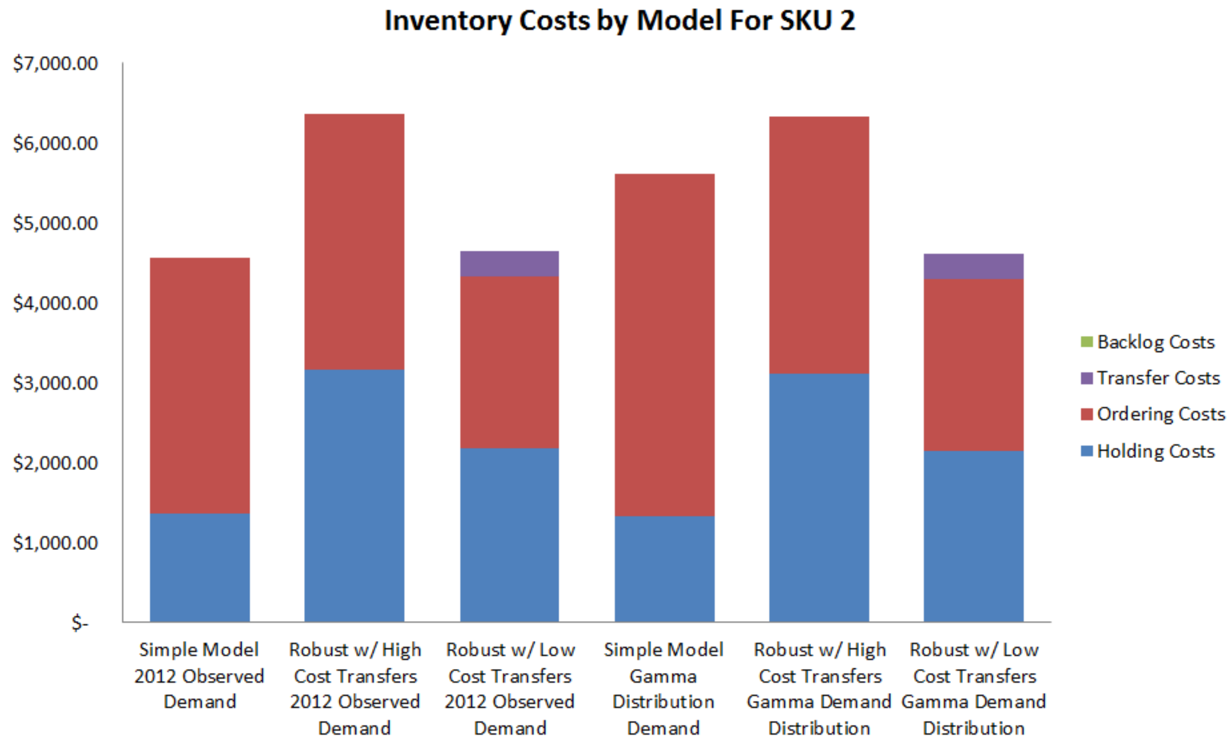


Figure 68 – SKU2 Total Inventory Costs for each Model with 2012 Observed Demand and Gamma Distribution Demand

Table 19 below shows that the balance between inventory holding costs and ordering costs for the simple model were less balanced based on the synthetic gamma distribution demand. The demand for SKU2 at CDC3 reached a total of 10 units in the ninth period which triggered one additional order in the tenth period. This order resulted in the 6% increase in ordering costs as a percentage of total costs for the simple model.

	Simple Model 2012 Observed Demand	Simple Model Gamma Distribution Demand	Robust w/ Low Cost Transfers 2012 Observed Demand	Robust w/ Low Cost Transfers Gamma Demand Distribution	Robust w/ High Cost Transfers 2012 Observed Demand	Robust w/ High Cost Transfers Gamma Demand Distribution
Holding Costs	30%	24%	47%	47%	50%	49%
Ordering Costs	70%	76%	46%	46%	50%	51%
Backlog Costs	0%	0%	0%	0%	0%	0%
Transfer Costs	0%	0%	7%	7%	0%	0%

Table 19 – SKU2 Inventory Costs by Percentage for Each Simulated Model Scenario

The final SKU with a small average demand value per period that we present is SKU4. Table 20 below shows the gamma distribution parameters for simulating demand in each quarter for each CDC.

	2011 Q1		2011 Q2		2011 Q3		2011 Q4	
	k	Θ	k	Θ	k	Θ	k	Θ
CDC1	0.28	5.92	0.36	1.40	0.63	1.86	0.61	1.22
CDC2	0.38	3.50	0.30	2.20	0.17	8.00	0.06	4.00
CDC3	0.30	2.20	0.42	1.60	0.36	1.40	0.25	1.00

Table 20 – SKU4 Gamma Distribution Parameters for each CDC

The resulting synthetic demand strings generated using the parameters from Table 20 are shown in Table 21 below.

2012 Observed Demand for SKU4

	CDC1	CDC2	CDC3
January	0	0	0
February	0	1	0
March	4	11	2
April	0	0	2
May	0	1	1
June	4	4	2
July	11	5	0
August	0	0	2
September	0	5	1
October	0	3	0
Total Demand	19	30	10

Gamma Distribution Demand for SKU4

	CDC1	CDC2	CDC3
January	0	1	5
February	0	1	2
March	0	25	0
April	0	2	0
May	2	1	1
June	0	0	1
July	0	2	0
August	2	0	0
September	13	1	0
October	0	2	0
Total Demand	17	35	9

Table 21 - Observed Demand and Gamma Distribution Demand for SKU4

The total inventory costs by model are shown in Figure 69 below. The number of orders, and the quantity of SKUs, ordered by the simple and the robust models were identical to the decisions observed with actual 2012 demand. This result is identical to the results seen previously for SKU1 using demand values developed from the gamma distribution. The only cost difference between the use of 2012 actual demand and demand developed from the gamma distribution was the holding costs. The higher total demand for SKU2 combined with the smaller demand values in the last two periods resulted in higher holding costs for all three models simulated with demand from the gamma distribution.

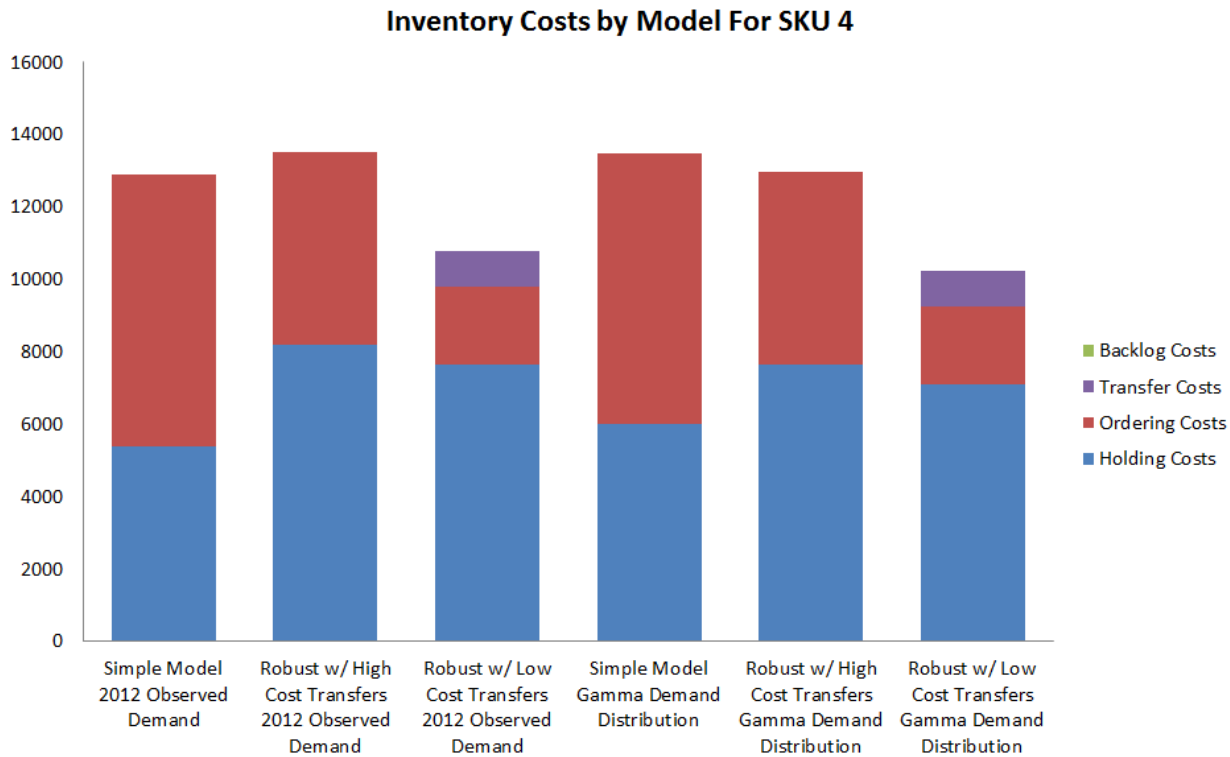


Figure 69 – SKU3 Total Inventory Costs for each Model with 2012 Observed Demand and Gamma Distribution Demand

Table 22 below shows that the balance between holding and ordering costs between similar models was less than 3% for any of the scenarios. The resulting balance between ordering and holding costs for each type of demand string was similar to the results observed for SKU1. These results indicate that the use of demand strings from the gamma distribution do not have a significant impact on the total projected costs of the models.

	Simple Model 2012 Observed Demand	Simple Model Gamma Distribution Demand	Robust w/ Low Cost Transfers 2012 Observed Demand	Robust w/ Low Cost Transfers Gamma Demand Distribution	Robust w/ High Cost Transfers 2012 Observed Demand	Robust w/ High Cost Transfers Gamma Demand Distribution
Holding Costs	42%	44%	71%	70%	60%	59%
Ordering Costs	58%	56%	20%	21%	40%	41%
Backlog Costs	0%	0%	0%	0%	0%	0%
Transfer Costs	0%	0%	9%	10%	0%	0%

Table 22 – SKU4 Inventory Costs by Percentage for Each Simulated Model Scenario

In this section we presented three SKUs with low average demand values per period in order to understand the impact of selecting simple model inventory policies based on normal demand distribution assumptions. Despite the use of the gamma distribution, we found the inventory ordering decisions suggested by all three models were almost identical to the decisions made based on actual 2012 demand values. Our preliminary conclusion is the use of normal assumptions for demand in the simple model have the potential to provide a reasonable approximation for inventory policies. This exercise does not provide insight into whether the robust formulation is better than the simple model formulation for Tracks Energy's needs, however it does highlight the importance of accurately projecting expected demand averages with reasonable levels of standard deviations.

6.4 Chapter Summary

In this chapter we presented a simple model based assuming lead time and demand follow the Normal distribution in each time period. With this model we were able to calculate new inventory policies, based on historical demand, to identify large potential savings through the use of more sophisticated ordering policies. We also presented a robust model that is designed to optimize costs given bounded unfavorable demand scenarios. This model was more complex than the simple model, because it must be run for each individual SKU and does not have a simple closed form formulation. The robust model demonstrated the value of using transshipments to drastically reduce total SKU inventory costs. We also compared the two models and discovered that unfavorable demand planning with a robust model was not significantly more expensive than a conservative simple model in the short run.

Based on the analysis presented in this chapter, the simple model is advantageous when the cost of stocking out of a particular SKU is similar for a large portion of the SKU catalog. The simple model provides a closed form formulation that can be easily calculated for a large number of SKUs through the use of a spreadsheet tool such as Excel. SKUs with low stock out costs, or short lead times, are the ideal candidates for this type of inventory policy modeling because the policies for a large quantity of SKUs can be calculated with a small time investment. These types of SKUs also provide the company with the ability to recover quickly from stock out conditions resulting from large demand variations. The robust model is more applicable than the simple model for SKUs that have very high stock out costs, very large demand variations, or long lead times. The ability of the robust model to cope more conservatively with unfavorable demand fluctuations, and forecast uncertainty, is important in the utility industry due to weather events and unplanned equipment failures. Since regulated utilities are primarily evaluated based on their customer service performance, ensuring inventory policies for long lead time items are conservative can help protect the company from large intangible political costs in addition to large stock out costs. The robust model does have a propensity to hold more inventory than the simple model, which can have significant cost implications if holding costs for material are high.

Our sensitivity analysis of the input variables showed that both models reacted similarly when holding and fixed costs were modified. As holding costs increased, both models planned to order material more frequently while decreasing inventory levels. Conversely, as ordering costs increased, both models favored holding more material to reduce the number of orders placed. We also concluded as the budget of uncertainty for the robust model increased, the model became more conservative and held more inventory to protect against potential stock outs caused by increased demand level. Finally, we showed that replacing actual 2012 demand with synthetic demand generated with a gamma distribution not have a significant impact on the inventory policies suggested by these three modes.

Chapter 7: Conclusions

Tracks Energy has been experiencing increasing inventory holding and purchasing costs since 2007, leading to a desire to develop a strategic supply chain roadmap to reduce costs. This thesis presents a methodology for developing a strategic supply chain roadmap suited to the needs of Tracks Energy. We developed process maps for current supply chain operations in order to properly understand material and information flows through the existing network. We conducted data analysis, primarily centered on inventory, in order to quantify the potential impact of resolving issues identified during the process map development exercise. We also used benchmarking data to evaluate current performance across a variety of supply chain metrics designed to outline the current state, and to serve as a tool for tracking performance improvements as initiatives identified as part of the strategic roadmap are resolved. The universal supply chain improvement framework of process map development, benchmarking, scorecard development, and future state definition can be used by any organization starting to look at their supply chain from a strategic perspective.

This thesis also presents two inventory models designed to be strategic tools for analyzing and improving existing inventory policies for capital and consumable materials. The inventory policy model based on stochastic demand and lead times showed the potential for significant inventory reductions without compromising service levels. The multi period robust model was not limited by a specific demand distribution, and highlighted the cost and supply chain performance implications of utilizing transfers to avoid fixed ordering costs. Both models demonstrated the benefit of increasing order quantities, thus holding more inventory, when fixed ordering costs are large. Conversely, both models demonstrated the financial benefit of decreasing inventories when the fixed ordering costs are small. More work is required to definitively conclude which model is better suited for Tracks Energy, but we believe that both of these models have potential merit for providing strategic direction to develop new inventory policies that improve responsiveness and performance. Inventory modeling can have significant financial implications, and should be considered when developing a strategic supply chain roadmap.

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