Optimizing Procurement and Handling Costs in a Utility

by

Bradley Philip Genser

B.S., United States Military Academy, West Point, 2007

Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of

Master of Business Administration

and

Master of Science in Mechanical Engineering

in conjunction with the Leaders for Global Operations Program at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2014

Signature redacted

Author ....

MIT Sloan School of Management and the Department of Mechanical Engineering

May 9, 2014

Signature redacted

Certified by ....

Bruce Cameron, Thesis Supervisor

Lecturer, Engineering Systems Division

Signature redacted

Certified by ....

Georgia Perakis, Thesis Supervisor

William F. Pounds Professor of Management Science, MIT Sloan School of Management

Signature redacted

Certified by ....

David E. Hardt, Thesis Reader

Chairman, Committee on Graduate Students, Mechanical Engineering

Signature redacted

Approved by ....

David E. Hardt

Chairman, Committee on Graduate Students, Mechanical Engineering

Signature redacted

Approved by ....

Maura Herson

Director, MIT Sloan MBA Program

Optimizing Procurement and Handling Costs in a Utility

by

Bradley Philip Genser

Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering
on May 9, 2014, in partial fulfillment of the
requirements for the degrees of
Master of Business Administration

and

Master of Science in Mechanical Engineering

Abstract

We propose a novel method to quantify the cost of activities involved in the picking portion of order fulfillment.

We adapt the general method of picking cost quantification to the specific situation of TP&G, a publicly held utility, to build a simulation model which calculates total cost (procurement purchasing costs + material handling costs) across TP&G's Construction Materials Supply Chain (CMSC) . We use the simulation model to demonstrate the effect of case pack quantities and various disputed (within TP&G) material handling policies on supply chain costs.

Finally. we move beyond the descriptive results of the simulation model and build optimization models for a case where a single case pack quantity is held in inventory, under conditions of both deterministic and stochastic demand. We show that case pack quantity held in inventory greatly impacts supply chain costs. We also find the novel result that the optimal material picking policy for both deterministic and stochastic demand is a threshold policy whereby orders should be fulfilled with whole case packs up to the highest possible multiple of case pack quantity that does not exceed an ordered quantity. If the remainder of an order to be fulfilled exceeds a certain number of units in a case pack, that remainder should be fulfilled with a whole case pack (overfilled). This threshold can be efficiently calculated for all case pack quantities (optimal or not).

Thesis Supervisor: Bruce Cameron
Title: Lecturer, Engineering Systems Division

Thesis Supervisor: Georgia Perakis
Title: William F. Pounds Professor of Management Science, MIT Sloan School of Management

Thesis Reader: David E. Hardt
Title: Chairman, Committee on Graduate Students, Mechanical Engineering

Acknowledgments

I want to thank everyone at TP&G for welcoming me into the organization and being so open and helpful to me as I conducted research. The management teams, and employees with whom I worked were by far my greatest resource in deciphering such complex operations. I am forever indebted to them for their generosity and support.

I also extend much gratitude to my thesis advisors, Georgia Perakis (Sloan Advisor) and Bruce Cameron (Engineering Advisor) for their support in technical areas and in shaping the research to develop a robust thesis.

Gonzalo Romero, a PhD student of Georgia's also deserves recognition for his technical support of my research. Gonzalo was always available to help with development of an idea from the most abstract mathematical formulation to mundane problems with implementation of the models, and for that I am forever grateful.

Lastly, I would like to thank my wife, Amanda, for encouraging me to pursue the LGO program, then supporting me through the program. Without her, this thesis would not be possible.

Disguised Information

This thesis is the result of research performed over a six-month period at a publicly held, regulated electric power and natural gas utility in the United States. As a result, much of the information the author acquired is sensitive in nature. To ensure proprietary information remains proprietary, the company's name has been changed. Additionally, sensitive information has been disguised through substitution of notional data and the masking identifiable sources.

Contents

1 Introduction **15**

1.1 Company Overview 15

1.1.1 Generation of Revenues 15

1.2 The Construction Materials Supply Chain (CMSC) 17

1.2.1 Suppliers 18

1.2.2 Central Distrbution Centers 19

1.2.3 Crew Barns 19

1.2.4 Job Sites 20

1.3 The Problem 20

1.3.1 The General Problem 20

1.3.2 A Specific Example of the General Problem 20

1.3.3 Important Terminology 22

1.3.4 Research Focus 22

1.4 Hypothesis and Contributions 23

2 Literature Review **25**

2.1 Chapter Description 25

2.2 Related or Similar Problems 25

2.2.1 The Assortment Problem 25

2.3 The Cutting and Packing Problem 28

2.4 The One Warehouse Multi-Retailer Problem 29

2.5 Warehousing Optimization 30

3 **The Total Cost Framework** **33**
3.1 Chapter Description 33
3.2 Total Supply Chain Costs 34
3.3 Purchasing Costs 35
3.4 Handling Costs 35
3.4.1 Overview 35
3.4.2 Relating Handling Costs to Worker Activity 36
3.4.3 Handling Tasks Considered 37
3.5 Total Cost Framework Conclusions and Extensions 40

4 **Adapting the Total Cost Framework to TP&G** **41**
4.1 Chapter Overview 41
4.2 Procurement Overview and Purchasing Costs 42
4.3 Demand 45
4.4 Handling Costs 46
4.4.1 Whole Case Pack Picking and Individual Unit Picking Costs 46
4.4.2 Breaking Open Packs Cost 47
4.5 Material Handling Policy Considerations 50
4.5.1 Rule of Thumb 51
4.5.2 Results of RoT 53
4.5.3 Cost of Unfulfilled Orders 53
4.5.4 Cost of Overfilled Orders (Misallocated Units Cost) 54
4.6 Building the Model 55
4.7 Simulation Assumptions 55
4.8 Simulation Indices 56
4.9 Simulation Inputs 57
4.10 Simulation Outputs 57
4.11 Total Cost Simulation Equation 57
4.12 Total Cost Sub-Components - General Case (Broken Packs Allowed) 58

4.13 Rule of Thumb (RoT) Algorithm 59
4.13.1 Calculating Misallocated Unit Cost 60
4.13.2 Rule of Thumb "Total" Cost 60
4.13.3 Model Implementation in Python 61

5 Case Studies - The Square Washer and Electric Cable **63**
5.1 Case Studies Introduction 63
5.2 The Square Washer 64
5.2.1 Description 64
5.2.2 Square Washer Basic Data and Observations 65
5.2.3 Results by Case Pack Quantities 65
5.2.4 Comparison of Optimal Case-Pack Quantity and Current Case-Pack Quantity Under Current Policies 68
5.2.5 Evaluation of Alternate Policy - Breakpack 69
5.2.6 Conclusions about policies and the Square Washer 70
5.2.7 Conclusions about Case-Pack Quantities for the Square Washer . . . 71
5.3 Electric Cable 71
5.3.1 Electric Cable Description 71
5.3.2 Basic Electric Cable Data 72
5.3.3 Results by Reel Size 73
5.3.4 Comparison of Optimal Reel Size and Current Reel Size Under Current Policies 74
5.3.5 Conclusions about Current Reel Sizes for Electric Cable 74
5.4 Case Study Conclusions 75

6 Optimization Models **85**
6.1 Indices 85
6.2 Parameters 85
6.3 Decision Variables 86

6.4 Objective Function 86
6.5 Constraints 87
6.6 Problem formulation 88
6.7 Choosing One Case Pack Size Only 88
6.8 Incorporating Demand Uncertainty: One Case Pack Size Only 92
6.9 Parameters 93
6.10 Random Variables 93
6.11 State variables 94
6.12 Control policies 94
6.13 Cost per stage 95
6.14 State transitions 95
6.15 Long run average expected cost 95
6.16 Optimal solution 96
6.17 Application of Single Case Pack Optimization to the Square Washer 100
6.18 Conclusions of Optimization 103

7 Conclusions **105**

7.1 Model Conclusions and Recommendations 105
7.1.1 Optimal Policy Conclusions 105
7.1.2 Optimal Case Pack Quantity Conclusions 105
7.2 Recommendations for TP&G Procurement 106
7.2.1 Implementation of the Model 106
7.2.2 Engaging Suppliers 106
7.3 Recommendations for TP&G Warehouse Management 107
7.3.1 Remove Rule of Thumb 107
7.3.2 Investigation and Development of Handling Procedures for Spooled Items 107
7.3.3 Investment in More Capacity 108
7.4 Recommendations for TP&G Executives 108

7.5 Conclusion 109

List of Figures

1-1 TP&G Construction Materials Supply Chain Overview 18

2-1 Overview of Warehouse Research by Category [5] 31

2-2 Composition of Material Handler's Time [7]] 32

2-3 Diagram of Warehouse Functions [4] 32

4-1 Road Cones in Use 43

5-1 Pictures of the Square Washer 64

5-2 Rule of Thumb: Washer Total Cost and Customer Service Level 77

5-3 Rule of Thumb: Extra Units Sent and Associated Cost 78

5-4 Rule of Thumb: Unfulfilled Units and Potential Costs 79

5-5 Total Cost Graph for "Breakpack" Fullfillment Policy 80

5-6 Representative Picture of Electric Cable Reel 81

5-7 Cable Total Cost and Customer Service Levels 82

5-8 Electric Cable Extra Units (ft) Sent and Associated Cost 83

5-9 Electric Cable Unfulfilled Units and Potential Costs 84

6-1 Conclusions of Optimization for Warehouse Managers 103

6-2 Conclusions of Optimization for Procurement Personnel 104

List of Tables

4.1 Case Pack Quantity Menu for Road Cones 43

4.2 Demand Data for Road Cones 45

5.1 Square Washer Basic Data 65

5.2 Square Washer Handling Cost Data 65

5.3 Square Washer - Case Pack Cost Comparison under 50% RoT 68

5.4 Square Washer - Case Pack Cost Comparison under Breakpack Policy 69

5.5 Electric Cable Basic Data 72

5.6 Electric Cable Handling Cost Data 72

5.7 Electric Cable - Case Pack Cost Comparison under 50% RoT 74

6.1 Square Washer - Cost Comparison of Optimal Threshold Policy and Satisfying Orders Exactly 100

List of Equations

1.1 Utility Revenue Requirement Formula 16

4.1 Total Handling Cost Equation 58

4.2 Calculation of Whole Case-Packs Used 58

4.3 Calculation of Whole Case-Packs Used 58

4.4 Calculating Number of Opened Case-Packs per order 58

4.5 Calculating Sum of Opened Case Packs for a Demand Array 58

4.6 Calculating Number of Individual Units Picked 59

4.7 Calculating Number of Individual Units Picked 59

4.9 Cost of Not/Partially Fulfilling Orders 60

4.10 Calculating Total Misallocated Units Cost for a given Case-Pack Size 60

4.11 Rule of Thumb Total Cost Equation 60

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 1

Introduction

1.1 Company Overview

Thunder Power and Gas (TP&G) Company is a large investor-owned electric power and gas utility focused on the transmission and distribution (T&D) of electricity and natural gas. TP&G's electric power and natural gas T&D networks operate in multiple states within the United States.

TP&G was founded approximately two decades ago and grew rapidly through the acquisition of many smaller publicly and privately owned utilities. Today, TP&G provides electric power and natural gas to millions of customers across multiple states and maintains thousands of miles of electric and gas T&D lines and associated infrastructure.

1.1.1 Generation of Revenues

Regulated utilities like TP&G interact with many consumers, but, unlike most customer oriented companies, TP&G cannot charge its customers whatever price it sees fit. TP&G and local regulatory authorities enter into a negotiation about what TP&G can charge. This negotiation is called "rate case." The negotiations usually occur at the state level or local government level. Regulatory agencies are represented by a Public Utility Commission (PUC) which is charged with negotiating the tradeoff between ensuring consumers in their districts receive reliable service at a reasonable (non-monopoly condition cost) while ensuring that utility companies can still earn a profit and attract outside capital for a reasonable cost. PUCs must also incentivize utilities to be efficient and continually invest in and build new infrastructure.

The ultimate output of a rate case is a maximum revenue which a utility is allowed to earn. The formula used to determine a utility's revenue is as follows

$$R = O + (V - D)r \tag{1.1}$$

Where:
$R \equiv$ Required Revenue (\$)
$O \equiv$ Operating Expenses (\$)
$V \equiv$ Gross Value of Assets (\$)
$D \equiv$ Accrued Depreciation of Assets (\$)
$r \equiv$ Allowed Rate of Return (%)

Operating expenses include all expenses such as personnel costs, supplies, and taxes. The operating costs are a fixed quantity. Any operating costs in excess of the rate case defined operating costs result in decreased returns to shareholders.

The rate of return in the equation is set by the PUC as well. A utility can earn a rate of return on its assets less depreciation. This gives the management of utilities incentive to continually invest in infrastructure.

A point that is particularly important in view of the overall analysis in this thesis is that all of the construction materials in a project cannot be capitalized as an asset until projects are completed. Before then, those materials are part of operating expenses. Thus, any delays in finishing a project mean that capital is locked up in the materials, but is not earning a return. This is an important point because this feature could have a large impact on costs of fulfillment policies. This will be outlined in later chapters.

1.2 The Construction Materials Supply Chain (CMSC)

TP&G owns and maintains all T&D infrastructure in its areas of operation. Accordingly, TP&G is constantly engaged with large scale construction projects to maintain current infrastructure, repair damaged infrastructure (e.g. in response to storms), and expand current infrastructure. Because TP&G grew through the acquisition of smaller utilities, the current infrastructure is very diverse in nature.

The infrastructure reflects the technologies, practices, and requirements of each area of operation despite the fact that the end product (a certain voltage of electricity or a unit of natural gas) is the same in all areas. For example, on the electric side, it may be cheaper (or less disruptive to customers) to maintain a 100 year-old transformer in a densely populated urban area than it is to build a new, more modern substation. On the gas side, a "legacy" gas company in one state may have chosen to build its infrastructure using a certain type of valve or piping while another state's gas infrastructure may have been built at a different time when different piping and valve technology was available. The regulatory requirements of each state also drive differences in the composition of T&D networks and infrastructure, because PUCs sometimes dictate that certain technologies be used in the area.

Maintaining thousands of miles of compositionally diverse electric power and gas T&D lines across multiple states in both day-to-day operations and emergency situations (e.g. hurricanes, gas leaks) costs billions of dollars per year and requires a constant and reliable flow of construction materials of all shapes and sizes ranging from inexpensive (e.g. nuts and bolts) to very expensive (e.g. bespoke electrical transformers or cable).

TP&G sustains their complex maintenance and construction operations through their Construction Materials Supply Chain.

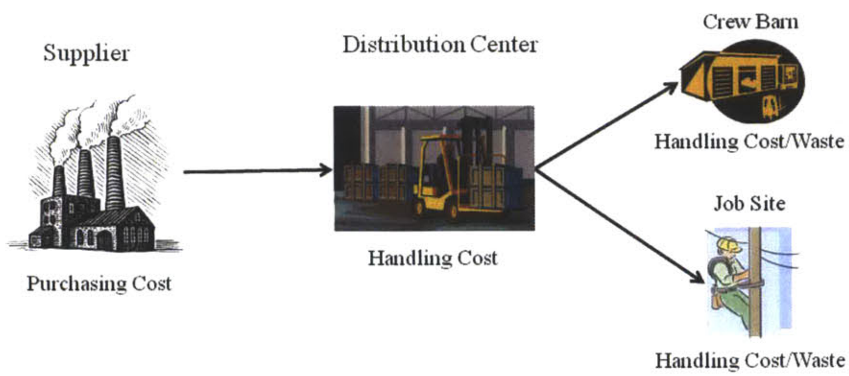


Figure 1-1: TP&G Construction Materials Supply Chain Overview

Figure 1-1 gives a pictoral overview of the CMSC and costs relevant to the thesis.

1.2.1 Suppliers

TP&G's suppliers are as diverse as the materials that TP&G holds in its warehouses. TP&G generally negotiates contracts with suppliers every one to three years through a low-bid sourcing process in which firms compete for contracts. It is entirely possible that a supplier could win a bid for one item and lose for another. For this reason, the supplier base is very large and very diverse. Suppliers can be large or small. Some are highly specialized manufacturers, while others are general distributors.

1.2.2 Central Distrbution Centers

Almost all goods purchased for use by TP&G flows through one of its Central Distribution Centers. The central distribution centers are very large warehouses that have receiving, stocking, and fullfillment functions within them. TP&G CDCs also have large outside storage yards for storage of large items such as transformers and large cable reels.

1.2.3 Crew Barns

Crew barns are small satellite facilities that serve a dual purpose as staging areas for work crews and small inventory sites that generally hold inexpensive multi-use items (such as nuts and bolts) and safety equipment. The inventory at these sites is, in some cases, managed by a dedicated employee who ensures the site remains stocked with needed materials and orders special materials on behalf of the work crews upon request.

The advantage of the crew barns is that work crews always have material available to perform their work near where the work is scheduled.

The percentage of total inventory held in crew barns is unknown. Once material leaves a TP&G CDC it is counted as expended in TP&G's ERP system. No systematic effort to catalog inventory levels at crew barns has been undertaken.

During our research, most employees involved with inventory and crew barns estimated the total dollar amount of inventory in crew barns between $50 MM and $400 MM.

There is no sure way to tell how much inventory is being held in these locations. The lack of information about crew barn inventory levels creates problems in times of material shortages in the CDCs. If for example, a CDC stocks out of a material, there may be stock piles of that material in a crew barn location, unbeknownst to inventory planners. That material could be transferred to where it is needed in these situations if the location and amounts of crew barn materials were known.

1.2.4 Job Sites

The central distribution centers will also send materials directly to job sites. Usually these are for large infrastructure jobs (such as replacing all the light poles in a neighborhood) or for jobs that are performed by contracted (i.e. Non-TP&G internal employees) construction crews.

The advantage of delivering directly to job sites is that, often for large jobs, the materials required are physically large, and the CDC has the resources to deliver it (such as semi-trucks and special loading equipment) and the CDC, therefore, relieves the crews of the need to coordinate those resources.

1.3 The Problem

1.3.1 The General Problem

The executive leadership of TP&G feels that leaders within individual sub-organizations act to achieve what is locally optimal at the expense of what may be optimal for the entire company.

The executive leadership wishes to more fully understand the dynamics behind these problems and to engage in a scientific experiment which proves that organizations within TP&G can work together more closely to achieve better overall results.

1.3.2 A Specific Example of the General Problem

Within TP&G's inventory and warehouse management organization, the personnel are under pressure to deliver a high level of service to operations crews and perfect accountability of inventory materials for auditors and power and gas industry regulators.

This pressure has led to the enactment of various material handling policies (to be outlined in subsequent chapters) which make handling materials easier for material handlers and improve ease of inventory integrity.

For example, warehouse managers want to minimize the number of items in the warehouse which are stored in opened packaging. By opened packaging, we are referring to original packaging from suppliers that has been opened and has a quanitity of material units less than that of what was originally in the packages. For example, TP&G inventory managers may order a certain reflective vest that comes from the supplier in boxes which hold ten vests per box. The boxes of vests are stored in TP&G warehouses until internal customers place an order for vests into the warehouses. The order could be for any whole number quantity greater than zero.

If an ordered quantity of vests is not a multiple of ten, then a material handler might open the box of ten and remove (pick) the desired quantity to fulfill the order. This action will result in a partially filled box of vests stocked in the warehouse.

According to warehouse management and material handlers, breaking open original packages to fulfill orders is unnecessarily burdensome to material handlers who are under extreme pressure to fulfill orders quickly. Additionally, warehouse managers feel that having open packages of material on the shelves makes inventory accountability more difficult because, in order to account for open packages, auditors and inventory accountability personnel must stop and count each unit individually rather than just count whole packages.

In the case of any individual item, the load may not be too burdensome, but when considered over the greater than 10,000 unique inventory items held in TP&G warehouses, the accountability problem can add up and become quite burdensome to warehouse personnel and auditors.

The policy of not opening boxes may lead to a high level of underfilled or overfilled orders to TP&G CMSC internal customers, resulting in dissatisfied customers or excess material costs, respectively.

In this case, what is locally optimal is likely not optimal for the entire supply chain.

1.3.3 Important Terminology

It is important to pause for a moment as we generalize our discussion to all items and review some important terminology. We will use "case pack" as a general term to describe packaging of a material. Case packs could be boxes, cartons, crates, spools, etc.

We will refer to a condition in which opened case packs are present in the warehouse as a "breakpack" condition (this term is commonly used within TP&G to describe opened packages and the perceived problems).

1.3.4 Research Focus

In accordance with the desire of TP&G executives to investigate the potential impact of sub-organizations within the TP&G CMSC working more closely together, we are focused on developing a solution that solves or mitigates the problems listed above and to demonstrate, through the construction of a quantitative model, the potential benefits of such a solution on a cost basis.

We desire to find a solution that can be easily implemented if it shows potential to significantly reduce total supply chain costs. Therefore, we will largely focus on policies or practices which can be adjusted effectively for little or no cost, and actually be implemented with little or no political issues.

While looking for the desired characteristics, we found that the procurement organization was an ideal place to search for potential solutions. The terms of procurement's contracts with suppliers are reviewed often and changes can be implemented very easily due to the small size of the organization. Procurement is also the most "upstream" member of the CMSC with which we could interact on a regular basis. This is important because all the other TP&G CMSC sub-organizations have to deal with the consequences of procurement decisions. Thus, the impact of any decision made in procurement will cascade through the inventory and warehouse management organization and the field operations organization.

1.4 Hypothesis and Contributions

In our analysis, we define a framework and methodology for quantifying material handling costs. We apply that methodology to build a simulation model of TP&G's CMSC costs. We use the simulation to evaluate the associated costs of various material handling policies employed within TP&G (i.e. allowing for breakpack conditions).

We apply the simulation model to case studies about two materials from TP&G inventory (a square washer, and an electric cable) to demonstrate the drivers of costs within the CMSC. We further use the simulation model to make recommendations about procurement and fulfillment operations through the suggestion of optimal case pack quantities and policies (for the given conditions at TP&G) and show that TP&G can achieve significant reduction in costs.

In Chapter 6 use our handling cost methodology to build an optimization model to choose a single optimal case pack size under deterministic demand. The main result is that the optimal material handling policy turns out to be a threshold policy by which guides the choice of whether to open a case pack and fulfill an order with indiviudal units, or to satisfy the order with whole boxes only. The optimal threshold policy can be efficiently computed using the order "remainders" which exist after all demand which can be satisfied with whole case packs has been satisfied with whole case pack.

We extend the optimization to include stochastic demand and show through the use of dynamic programming and application of Bellman's equation that the optimal policy is a static threshold policy based on the components of handling cost.

Our results can be employed by TP&G and, more generally, to any organization which purchases, handles, and distributes materials for operations.

Chapter 2

Literature Review

2.1 Chapter Description

In this chapter, we will provide an overview of available literature related to our hypothesis and research.

2.2 Related or Similar Problems

Researchers have addressed many complex problems in inventory and warehouse management. On the surface, there are several "classic" operations research problems which bear similarities to the research presented in this thesis.

2.2.1 The Assortment Problem

Pentico [6] defines the assortment problem as follows:

> We are given a set of sizes or qualities of some product and their known or expected demands. Because of storage or manufacturing limitations, economies

of scale in production or storage, or the costs associated with holding different sizes in stock, a subset of the sizes will be stocked. Demands for an unstocked size are filled from a larger stocked size with an associated substitution cost. The problem is to determine that particular subset of sizes to stock that will minimize the sum of all relevant costs.

The problem addressed in this thesis is, at its heart an assortment problem, as defined by Pentico. TP&G warehouses (and all warehouses for that matter), have storage limitations due to physical constraints, and information technology constraints.

Pentico [6] identifies several variations of the assortment problem which commonly occur in the current literature. He categorizes the assortment problems as having the following problem characteristics:

- Demand - deterministic vs. stochastic.
- Demand Pattern - discrete vs. continuous.
- Dimensions - one vs. multiple.
- Number of sizes to stock - fixed vs. to be determined.

Similarities to Researched Assortment Problems

Using Pentico's categorization of the assortment problems, the problems we seek to address within TP&G can be categorized as follows:

Demand

In this thesis, we will address a problem with deterministic demand patterns as well as stochastic demand.

Demand Pattern

The demand patterns are discrete in nature. All customers must place orders that are positive integers.

Dimensions

We take a one-dimensional approach to the presented problem. We are interested only in the determination of the optimal case pack quantity for a given item to be held in inventory. We do not address the problem of determining the overall quantity of an item to be held in inventory to satisfy demand. We assume that stocking levels are predetermined. We are answering the question of the composition of case packs that should compose the desired stocking level.

Number of Sizes to Stock

We will evaluate a case in which one size is stocked. The one size only is the one faced by TP&G and is relevant to many businesses. The fixed number of sizes to stock is realistic for the environment in which this research was performed, because the information technology complexity increases greatly with the number of sizes stocked.

Standardization and Adaptation Losses

Bongers [2] puts forth mathematical frameworks to select sizes of a product based on the minimization of adaptation losses - losses stemming from a customer receiving a standard size rather than the size they actually need. These losses could be trimming losses asin the case of steel beams which must be cut to a useable size by construction crews, or the cost of being uncomfortable if standard shoe sizes are too big or too small.

There are similar dynamics between our problem and the standardization problem as presented by Bongers in that costs are incurred by TP&G when orders from internal customers do not match exactly the case pack quantities held in TP&G's inventory and we wish to define a "size pattern" which minimizes those costs.

Bongers' analysis is aimed at answering the question: If I am a supplier of a product, what assortment of sizes should I produce?

Our analysis answers the question: If I operate a distribution center and do not manufacture goods, what size should I choose, and what is the optimal handling policy for that size?

We move from theoretical loss functions and build our own adaptation loss functions based on the reality of picking.

We also employ real demand data and a dynamic programming approach using Bellman's equation as outlined in Bertsakis Vol. II [1] to compute an optimal solution from discrete demand patterns. Bongers does not use dynamic programming, and assumes a pattern sampled from a continuous distribution.

2.3 The Cutting and Packing Problem

Wäscher et al. [9] identifies the general cutting and packing problem as having the following form and characteristics:

Given are two sets of elements, namely

- a set of large objects (input, supply) and
- a set of small items (output, demand),

which are defined exhaustively in one, two, three or an even larger number (n) of geometric dimensions.

Select some or all small items, group them into one or more subsets and assign each of the resulting subsets to one of the large objects such that the geometric condition holds, i.e. the small items of each subset have to be laid out on the corresponding large object such that

- all small items of the subset lie entirely within the large object and
- the small items do not overlap, and a given (single-dimensional or multi-dimensional)objective function is optimised.

Our addressed problem is, in part, a cutting and packing problem.

The set of large objects for us is supply, and the set of small objects for us is demand. We provide two sets of supply objects from which to serve demand: units served in whole case-packs and individual units picked from open boxes.

Our goal is to serve demand at the lowest total cost (procurement + handling costs).

We are, however, not constrained by meeting demand exactly in our problem. Instead, we can relax that constraint and provide more units of a material than are ordered. Indeed, we show that overfilling orders is, under certain circumstances the optimal fulfillment policy.

2.4 The One Warehouse Multi-Retailer Problem

Our setting is similar to the classic One Warehouse Multi-Retailer (OWMR) problem - a problem in which a single central warehouse exists from which multiple retailers (smaller inventory sites) order. The one warehouse multi-retailer system as presented in this problem is representative of the TP&G system - the central distribution center is the one warehouse and crew barns are the retailers.

However, the similarity between our problem and the "classic" OWMR problem ends there. The OWMR problem objective is to decide the warehouse and retailers orders to minimize the fixed ordering costs plus the inventory holding costs over the planning horizon, see Zipkin [10] for a review of the classical results of this model.

In contrast, we incorporate the case pack type/quantity as a decision variable, and we introduce a novel way to explicitly model the handling costs incurred when using a given case pack quantity to serve orders.

Our work complements the OWMR problem solutions. We consider a fixed inventory policy (as mentioned in the assortment problem section), based on the fact that the decision about which case pack quantity to carry in inventory does not affect the overall quantities purchased, only the composition of that quantity. This allows us to simplify the problem and to focus on the tradeoff between purchasing and handling costs, or just how case pack quantity impacts handling costs.

There is little work in operations management that considers the case pack as a decision variable. Cachon and Fisher [3] show that supply chain cost reduction can be achieved through using smaller case packs, in the context of an assortment planning model with substitution. Van Donselaar et al. [8] present an empirical study of the ordering behavior of retail store managers. The results show that managers deviate more from ordering advice presented by an ordering system for products with larger case packs.

In contrast to these works, we show that a smaller case pack quantity is not always better, because selection of a smaller size may result in high handling costs.

2.5 Warehousing Optimization

Our work revolves around optimizing across the supply chain, to include the warehouse. For our work in which we are optimizing purchasing costs and handling costs within the warehouse, we make the assumption that routing is optimized to minimize travel times and that other supporting warehouse functions are optimized. This allows us to focus our analysis on the impact of case pack quantities and fulfillment policies on costs.

Gu et al. [5] provide a survey of existing literature regarding warehouse operations.

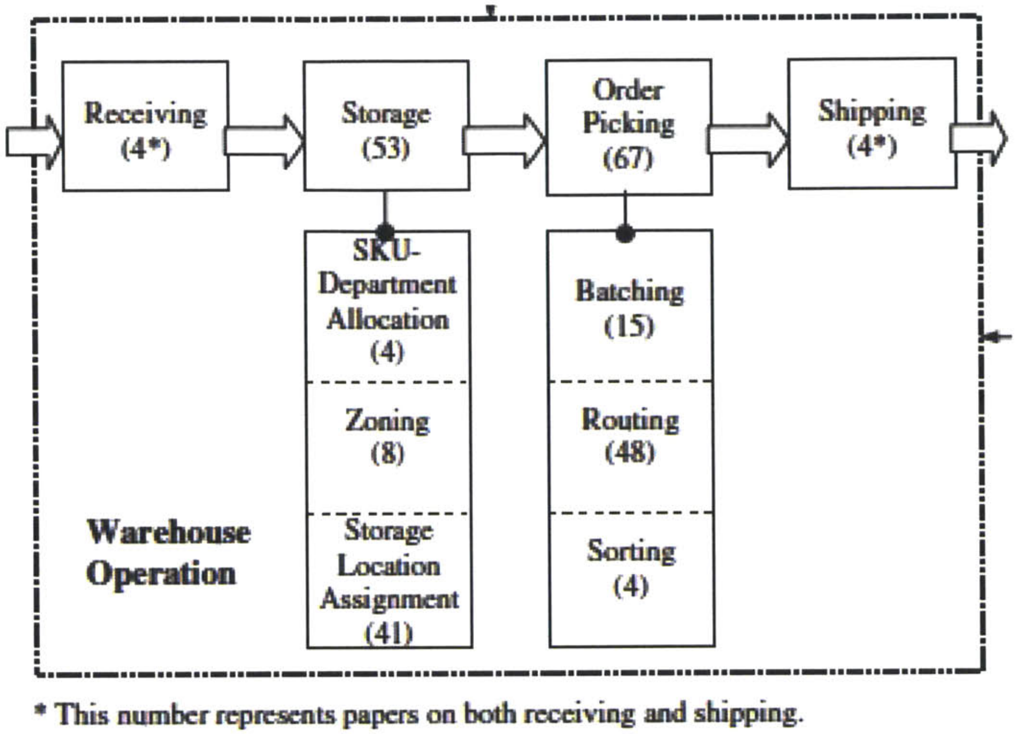


Figure 2-1: Overview of Warehouse Research by Category [5]

Figure 2-1 shows the number of papers in the surveyed set of literature by topic. Much research has revolved around Routing (48 papers) and Storage Location Assignment (41 Papers).

Despite all the research revolving around warehousing operations, no reviewed literature is devoted to quantifying the cost of picking beyond the routing or travel portion. Gu's work and Figure 2-1 corroborate our findings of no research in the area of picking beyond routing.

Despite the lack of picking focused literature, much of the existing literature acknowledges that picking is a significant task in warehousing operations.

Tompkins et al. [7] present an analysis of how material handlers spend their time. Figure 2-2 shows this analysis. Figure 2-2 shows why so much existing literature revolves around routing: that is how picker's spend much of their time. Picking time still takes up a significant amount of their time, however, at 15%. This, of course, is in a picker-to-parts system in which the picker travels to shelves. In a parts-to-picker system, which are becoming more

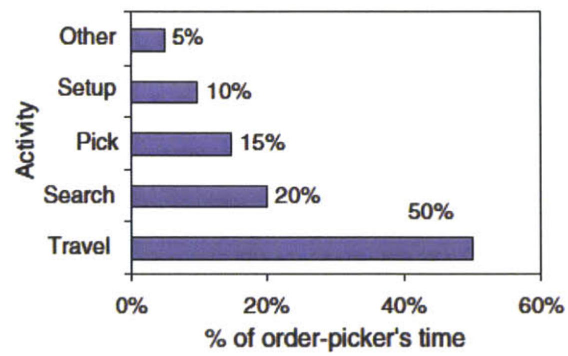


Figure 2-2: Composition of Material Handler's Time [7]]

popular, picking would occupy the majority of a material handler's time. Our research is relevant to both systems.

Tompkins' analysis is oriented towards planning optimal facilities and he does not delve deeper into optimization of picking.

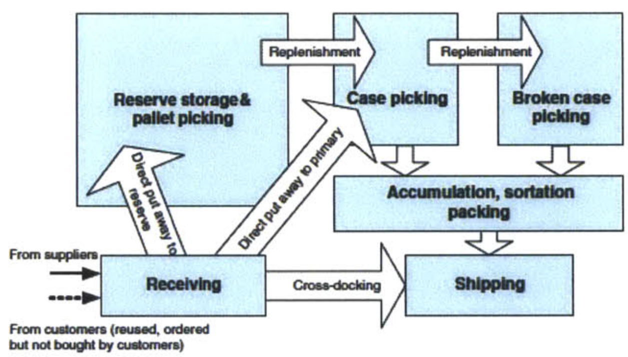


Figure 2-3: Diagram of Warehouse Functions [4]

de Koster et al. [4] acknowledge that broken case picking is a phenomenon that must be considered, but do not delve further into the problem beyond mentioning that it exists. Figure 2-3 shows that de Koster at least acknowledges that picking tasks are a consideration.

Quantification of handling costs beyond routing is not the main focus of our research, but is required for our purposes. We introduce a framework for quantfying handling costs in Chapter 3.

Chapter 3

The Total Cost Framework

3.1 Chapter Description

In this chapter, we present a flexible and adaptable framework for measuring and accounting for supply chain costs as a function of case pack quantities. We use the assumptions presented in this chapter to build models to simulate, analyze, and ultimately optimize costs throughout the supply chain as a function of case pack quantities held in inventory.

The particular set of considerations and assumptions presented within this chapter are inspired by conditions within TP&G, but are applicable to any company which employs a similar supply chain structure and warehousing operation. The framework can be easily adapted by adding or removing layers as needed.

In subsequent chapters, we adapt the framework presented here to TP&G-specific policies in order to simulate costs within TP&G's CMSC and demonstrate the effects of those policies on supply chain costs.

3.2 Total Supply Chain Costs

We are interested in developing models to describe the cost impact of decisions about case pack quanitities across the supply chain. For a given material, case pack quantities impact or potentially impact purchasing costs in procurement. Downstream in the supply chain, case pack quantities impact handling costs. The discussion of cost impact of case pack quantities revolves total cost as defined by the following equation:

$$\text{Total Cost} = \text{Procurement Costs} + \text{Handling Costs}$$

This relationship is simple, intuitive and very general.In any business, we are interested in maximizing profits which requires simultaneous goals of revenue maximization and total cost minimization. In many organizations however, there may be localized incentives to minimize only one component of cost that leads to a sub-optimal total cost.

For example, procurement for most organizations is generally charged with purchasing materials required for operations at the lowest possible per unit cost while still meeting quality requirements and safety standards. Suppliers are incentivized to sell as much material as they can at the highest possible margin.

The goals of both suppliers and procurement personnel usually result in the purchase of large case pack quantities of material. The large case pack allows for suppliers to realize their goal of selling more material at higher margins. The costs of packaging generally do not scale with case pack quantity (i.e. producing a box to hold 500 screws is marginally more expensive than producing a box to hold 100 screws). The supplier will generally pass on some of the higher achieved margin in the form of a per-unit discounted price, which allows procurement personnel to realize their goals.

All of this negotiating is done with no regard for how the larger case pack size impacts downstream operations.

In subsequent sections, we will expound upon each of the components of total cost important to our analysis and discuss other localized incentives.

3.3 Purchasing Costs

Purchasing costs are the up front cost of acquiring materials from a vendor.

Purchasing costs can and will vary according to purchased case pack quantities. This is reasonable and expected. For example, if a particular vendor manufactures safety cones and packages them in stacks of 15, and TP&G procurement requests packages of 10, then the vendor will incur some costs to accomodate the request, and will pass those on to TP&G and likely also charge a fee for the service in excess of the incurred cost.

There are no components to purchasing cost, only a per-unit or per-case pack cost that varies with case pack quantity depending on specifics of a modeled scenario.

3.4 Handling Costs

3.4.1 Overview

We will use the term "handling cost" to describe the marginal cost of fulfilling an order from a TP&G CMSC customer (e.g. job site or crew barn). For any order, a material handler will have to, at a minimum, travel to a material holding location and pick some quantity to fulfill an order. We are concerned with only the monetary cost expended by a worker for fulfilling a single order at the point that he picks the order from the shelf and moves on to fulfill the next material in an order.

We are interested in only the actions upon a material handler's arrival to a case pack of material because these are the only ones which are impacted by the case pack quantity. We showed in Chapter 2 that the current literature covering the optimal routing of a material handler to a location is quite extensive and that travel accounts for quite a bit of time (and therefore cost). Worker routing is not in anyway affected by the case pack quantity held in inventory. The only time impacted is the time in which the worker is directly handling a case pack to fulfill an order. The worker is only handling a case pack in the time between when he arrives at the shelf where material is stored and when he leaves that shelf.

For a material handler, the least time-intensive picking situation would be one in which the ordered quantity exactly matches the available case-pack quantity. In that special case, the worker can pick one case-pack of material and move on to fulfilling the next line-item in an order. If the ordered quantity does not exactly match the case pack quantities held in inventory, the worker can pick whole boxes up to a multiple of case pack quantity that is less than or equal to the ordered quantity. If picking whole boxes to the nearest multiple less than the ordered quantity does not satisfy the ordered quantity, then the material handler must open a case-pack of material and pick individual material units out of that opened case pack until the ordered quantity is fulfilled.

3.4.2 Relating Handling Costs to Worker Activity

In order to analyze any tradeoff between case pack sizes purchased and handling costs, we must be able to quantify handling costs.

All companies have employees and pay those employees for their time and talents. At TP&G all material handlers are paid an hourly wage that does not change except with new large-scale union negotiations. An hourly wage is a price per unit of time. Therefore, we can calculate the cost of any material handling task by multiplying the hourly wage by the amount of time required for the task.

$$Task\ Cost = Task\ Time\ x\ Hourly\ Wage$$

We know worker's wages from company payroll data and union data. To find time required to complete a given task, we set up a series of experiments and analyzed the data from those experiments to find a mean completion time (the mean may not be the most appropriate measure, but the framework stands no matter the measure).

It is important to note that this analysis is only useful if workers are fully engaged in work every second that they are on the clock (i.e. no sitting around waiting for work). If workers are not fully engaged in work and there is no potential chance of workers being fully engaged, then any optimization to ease worker's burden is, from a cost-focused perspective only, unimportant.

If a worker is never working at capacity, then there is no opportunity, within the realm of material handling, to increase his productivity per hour and thereby realize savings through reduction of hours worked.

TP&G's workers, however are fully engaged in handling material every second of their shifts with the exception of specified breaks every few hours. Speaking generally, most companies with warehousing operations have workers who are fully engaged in material handling activities full-time or are subject to peaks in demand in which workers will be fully engaged for some time period.

3.4.3 Handling Tasks Considered

Now that we have set the foundation for how we will relate handling costs, we will now define those costs that are important to our analysis.

As previously stated, our analysis is concerned only with only the monetary cost expended by a worker for fulfilling a single order at the point that he picks the order from the shelf and moves on to fulfill the next material in an order.

When a worker arrives at the area from which he will pick an ordered item, he is limited to three actions to fulfill the order and satisfy demanded quantities:

1. Satisfy demand with whole case-packs of material (i.e. box, carton, reel)
2. Satisfy demand with a combination of whole case packs of material and individual sub-units (i.e. individual units, smaller packs within the delivered case pack)

The process of satisfying demand with individual units actually requires two steps:

1. Accessing individual units, usually by opening a case-pack
2. Picking individual units

These two modes of satisfying demand can be broken into three timeable and, therefore, cost calculable tasks for a given material[1]:

1. Picking Whole Case-Packs (C)
2. Opening Case-Packs (K)
3. Picking Individual Units (V)

Picking Whole Case-Packs

The process of satisfying demand with whole case packs of material is self-explanatory: the material handler picks whole boxes of material until he reaches the ordered quantity of materials.

There is no or very little variation in the amount of time required to pick a whole case pack of material. For example, for a given box of screws, the boxes do not vary in size, shape, or weight. Therefore, picking one box of screws is exactly like picking any other box. This is important to note because, this may not always be the case. For example, if a certain supplier has lax quality standards then, with some probability, a box of screws could break when picking it and a time-consuming clean-up operation might ensue. For our purposes,

[1]Notations used in model formulation representing the cost for each are presented here with the identified cost categories.

though, we assume that the case packs are of high quality and indistinguishable from one another.

It is important to note that the time required to pick whole case packs scales linearly. We assume that workers do not suffer significant degradation in their ability to pick whole boxes and, thus, there is no variation in time from one box to the next. This is a reasonable assumption because fatigue tends to be the reason why picking multiple boxes might vary in time. We have not seen situations where workers fulfill such a large order that they become fatigued by lifting a large number of case packs. In situations where fatigue might be an issue, the workers typically use special equipment, such as fork lifts.

Opening Case Packs

Opening a case pack is a physical action that requires a worker to access a tool, such as a knife, and open the pack. The time this action takes varies depending on the tools required and complexity of the packaging. Intuitively, tearing open a plastic bag to access units requires no tools and little time. Opening a wood crate that has been nailed shut requires considerably more effort than opening a plastic bag.

The physical task is only one component of opening case packs. There exists the possibility of a penalty for opening packs that can be charged to this task. We allow for this penalty because there is a potential cost and new complexities introduced by conditions where open case packs are stored with unopened case pack. For example, once a case pack has been opened it often does not have the same structural integrity that it had when unopened. Therefore, other case packs cannot be stacked on top of it, potentially increasing the amount of time shelf stockers take to restock shelves in a warehouse. In building the TP&G simulation model, we will cover a specific example of how the costs of breaking open case packs in the warehouse extends far beyond just the cost of the physical act of opening the boxes.

Picking Individual Units of Material

The third cost category involved in calculating the marginal handling cost as a function of packaging size is picking one unit of individual material. Again, using the task-wage framework, we can time how long a material handler takes to pick one unit of an item and relate that to cost. For a small piece of hardware such as a nut, picking one unit can be performed easily. Picking a single unit of a large gas valve, however, may require special equipment or multiple people.

Picking multiple units scales linearly.

3.5 Total Cost Framework Conclusions and Extensions

The general framework we presented in this chapter is the basis of the subsequent models presented in our work. As we stated before, we built this framework within the context of TP&G, but this framework can easily be adapted to the specifics of any company which performs purchasing and warehousing operations.

In Part II, we demonstrate the flexibility of this framework by adapting it to build a TP&G-specific simulation model with which we can demonstrate the effects of case pack quantity decisions and various material handling policies. This allows us to provide conclusions and recommendations backed by quantitative analysis to TP&G executives.

In Part III, we adapt this framework to optimize costs and discuss the results.

Chapter 4

Adapting the Total Cost Framework to TP&G

4.1 Chapter Overview

In Part I, we presented the total cost framework to show the general method by which we will analyze costs as a function of case pack quantities held in inventory. We stated that the presented framework is adaptable to specific situations.

In Part II, we adapt the framework to TP&G's supply chain in order to gain insight into the current state of total cost in a rigorous and quantitative way, inform executive decision making regarding case pack quantities and picking policies, and to assess the feasibility and results of the presented framework in a real world case.

In this chapter, we highlight TP&G's specific circumstances that influence the simulation model in Part II. We state assumptions along the way and end the chapter by presenting the mathematical formulation of the simulation model.

In later chapters, we build case studies around a few inventory items using the simulation model and present the results.

4.2 Procurement Overview and Purchasing Costs

Procurement Process Overview

TP&G purchases all materials from outside vendors. TP&G divides its construction materials into "material groups" of similar items. For example, all gas pipe fittings and supporting materials are generally sourced in one "sourcing event." Sourcing events are essentially lowest bid (subject to quality requirements) competitions in which the supplier who can provide a material under TP&G's terms at the lowest price wins a contract to provide the item to TP&G for a certain length of time.

Materials are generally contracted for one to three years at a fixed per-unit price. Some contracts do allow for purchase price variance based on underlying commodity prices. This arrangement is most frequently used in copper cable and wire products and is unimportant to our analysis, since nothing about the final product delivered changes.

Procurement Personnel Performance and Incentives

Procurement personnel are assessed on their ability to negotiate minimum cost contracts with suppliers. The supply chain cost minimizing case pack quantity may not be the procurement contract cost-minimizing case pack quantity. This is not to say that procurement personnel do not wish to do what is best for the whole organization, but that in the absence of information about how purchasing case pack quantities affects the CMSC, they will default to negotiating contracts for the lowest cost possible.

Range of Available Case Pack Quantities

For many products, suppliers will offer several choices of case pack quantities. For example, if TP&G wants to purchase orange road cones (which are used frequently at construction sites to alert motorists to the presence of a TP&G construction crew see Figure 4-1), they

Figure 4-1: Road Cones in Use

may have the choice to do so in stacks of 5, 10, or 20 cones. That menu of sizes is represented in the following table:

Case Pack Type	# Cones per Pack	Price Per Pack
1	5	$25
2	10	$50
3	20	$100

Table 4.1: Case Pack Quantity Menu for Road Cones

It is also entirely possible that for some custom-made items, TP&G may dictate the packaging type to the supplier. In order to choose the best size, procurement personnel can create menus of their own sizes. We take this approach in the simulation case studies presented in Chapter 5.

We use the following notation to represent size menu data:

$j \in \{1, \ldots, m\}$: packaging types available from the supplier

$S_j=$ number of units in a box of packaging type j

Purchase Price Variance Based on Case Pack

We set out to understand how purchasing prices varies as a function of case pack quantities. We found that understanding the relationship between case pack quantity and purchasing price is not straightforward and we have failed to ascertain useful data regarding actual purchase price variance as a function of case pack quantity.

Our failure to ascertain the nature of purchase price variance is largely due to the fact that attaining pricing data would require earnest negotiations between TP&G and its vendors. Negotiations such as these would be special circumstances that would require a lot of dedicated resources for TP&G procurement personnel and TP&G suppliers. This level of commitment, understandably, requires some proof of benefits before deployment of those resources. In light of this, we (in conjunction with TP&G managers) decided to proceed with the development of a simulation model with the assumption that there is no purchase price variance.

By assuming that there is no purchase price variance, the simulation model does not capture the dynamics of the tradeoff between procurement costs and handling costs. This does not, however, prevent the model from showing how current and potential case pack quantities and picking policies compare in total cost. It is through the use of the simulation model that we can assess whether management should commit resources to engaging suppliers to understand price purchase variance.

Assortment of Case Packs Policies

It is possible that for a given item, TP&G could stock multiple case pack quantities of a given material. In practice, though, this does not happen, and it is not very feasible given the software architecture that governs the layout of materials in the warehouse and the routing of pickers.

The inventory and warehouse management software will assign a different material number to case packs of different quantities even if it is the same material. Customers are forced to order specific material numbers and, even if the customer is better served by an assortment of case pack sizes, the material handler must serve the order from that material number, and the associated case pack quantity. Further exacerbating this problem, the different case pack quantities would likely be placed in the warehouse nowhere near each other in accordance with layout planning software.

These software conventions are non-trivial to overcome, and, like negotiations with suppliers, would require a commitment of significant resources. Therefore, we will only consider holding one case pack quantity in the simulation model.

In this chapter, we have covered relevant aspects of the current state at TP&G as they relate to adapting the total cost framework to a simulation model.

We highlighted the areas where we are short of information, how we dealt with those shortages, and the implications for the model.

In the next chapter, we lay out the mathematical formulation of the TP&G model inclusive of all the considerations evaluated in this chapter.

4.3 Demand

For the purposes of our model, we take a demand vector (D) full of individual orders (i) of individual units to calculate associated costs. For example for a set of road cones which are stocked in sealed stacks of 10, a demand data will look like:

Order #	Units Ordered
1	10
2	7
3	22
4	20
5	10
6	2
7	17
8	13
9	2
10	10

Table 4.2: Demand Data for Road Cones

For the above table $D_1 = 10$, $D_2 = 7$, $D_3 = 22$ and so on up to the nth order. In this case, $n = 10$. We have shown a simple example of a demand vector (D) to show the form and function of the demand data we are using and how we will describe that demand data for subsequent calculations. Actual demand vectors for items across the supply chain can range in length from a few orders over a year, to thousands of orders over a year, but the form remains the same. There is an order number (i) and a number of units ordered (D_i) for that order number.

We define the following symbols and indices related to demand for use in our simulation:

$i \in \{1, \ldots, n\}$: orders received from crew yards or projects

D_i= number of units ordered in order i

4.4 Handling Costs

4.4.1 Whole Case Pack Picking and Individual Unit Picking Costs

In order to quantify whole case pack and individual unit picking costs, we performed many time trials of whole case packs and individual items being picked and calculated the mean time for various items and multiplied that mean time by the wage.

The time required to pick a case pack or individual material unit is directly a function of its weight. Intuitively, lighter items are more quickly picked by an individual worker. Heavier items may require two workers, and the heaviest items require special equipment(and more time to retrieve that equipment).

For items featured in case studies, the weights of the items are known, so we are able to calculate total case pack weights and, therefore, understand the tasks involved.

We represent the costs associated with picking a whole case pack and an individual unit of a given material with the following notation:

C_j= cost incurred in picking a *whole* box of packaging type j

z_j= whole case packs of type j used to satisfy all i

V= penalty (variable cost) incurred when picking a single unit from any opened box

u_j= number of individual units picked from open packages of type j to satisfy all i

4.4.2 Breaking Open Packs Cost

We stated in Chapter 3 that breaking open packs includes the task of opening the pack, and any potential penalties for problems associated with having broken packs.

The cost of the task of opening a pack is measured in the same experimental way as the picking of whole boxes and individual units.

Assessing the cost of having open packs is not as straightforward and introduces a complex web of incentives, and follow on tasks which we explain in this section. We will introduce background information for the reader to understand the problems with having what TP&G workers call "breakpack" conditions.

Cycle Counting Explained

TP&G is required by regulators to account for every item within their held inventory according to a certain schedule. The most frequently counted items must be physically accounted for four times per year, and the lowest category counted at least once per year. The origins or the merits of the regulations that require this are not essential to the study. But the existence should be noted because it does affect material handling costs.

Accounting for all items is performed through a process known as "cycle counting." Cycle counting involves a material handler manually counting the quantity of a given item in stock. The assigned material handler must go to the physical location of an item to be counted, and count the items. The material handler, then, enters his counted quantity into a hand held device linked to TP&G's ERP system. If the material handler's count does not match the quantity in the ERP system, the material handler is notified that the count does not match, but the notification does not indicate whether the manual count is above or below the quantity in the ERP system. This is a fraud prevention measure to keep material handlers from entering the correct count in the name of expediency. The ERP system will, then, direct the material handler to the next item to be counted, and usually, after a few other counts, return the material handler to the miscounted item for a recount. This cycle can be repeated up to 3 times, at which point, the material handler must notify his managers of a problem and the managers must take some corrective action to deal with the missed count. The corrective action is usually to confirm the counted quantity and subsequently update the ERP system with the quantity on hand.

Cycle Counting and Breakpack Conditions

The existence of opened case packs in the warehouse significantly increases the time required for cycle counting. Imagine cycle counting for a bolt. If only whole case packs of, say, quantity 100 are on the shelf in a warehouse, then the cycle counter need only count the number of boxes on the shelf and multiply by 100 to get the full count. The chances of missing a box are minimal, and management and the cycle counter have high confidence in the accuracy of the physical count.

Now imagine a situation where open packs of bolts are on the shelf as well. The cycle counter can no longer quickly count boxes and move on. He must individually count every bolt in the open boxes. This is a process that is highly prone to error, and neither the cycle counter, nor management can have high confidence in the accuracy of the count, usually requiring more time to be devoted to the problem.

Not only does a breakpack condition undermine confidence in the count, as described above, but it also increases the likelihood of actual material losses (particularly in smaller items). As an example, the bolts from above can easily be dropped or fall out of open packages during handling, further exacerbating inventory integrity problems.

Breakpack Conditions and Auditing

The issues presented in cycle counting also apply to inventory audits that are required to certify TP&G's financial statements. Auditors must endure the same problems that material handlers do during cycle counts if broken packs are in the warehouse. The reader might chuckle at the thought of a bunch of accountants standing around counting individual bolts, but the accountants do not have high confidence in their counts, and may be reluctant to certify that TP&G has the inventory they say they do.

If external auditors are unable to confirm inventory accuracy, and filed a letter saying so, then TP&G would be required to disclose such information in its annual report. This could potentially be a disaster for TP&G's stockholders.

Accounting for Breakpack Conditions

As we have seen, the breakpack issue is somewhat complicated particularly in TP&G's case due to a high level of regulatory scrutiny.

For the purposes of the model's cost calculations, the cost associated with the material handler's constant recounts is an obvious cost associated with breaking packs that can be timed and, thus, added to handling cost through the task-wage calculation as previously outlined.

Because breakpack conditions increase the exposure of an organization to a whole host of issues as outlined, and the impact of those issues is highly variable and could provide ample fodder for whole theses themselves, we have generalized the model to include an adjustable "breakpack penalty" that can be added to the costs of the physical act of opening a box. The penalty includes the cost of revisiting counts during cycle counting, and everything up through loss of market capitalization for stockholders.

The breakpack penalty could range anywhere from $0 (e.g. perfect handling process control) to millions of dollars (e.g. decline in stock price due to lack of investor confidence in financial statements).

For our calculations, we will use a breakpack penalty towards the lower end and apply our task-wage framework. We observed many cycle counts during our time at TP&G. In our experience, 100% of counts were correct when only whole case-packs of items were stocked. On the other hand, we never once saw an accurate count when partial packages of a given item were present.

We acknowledge (but highly doubt) the possibility that we were present at TP&G during a time in which the results (or lack of results) from cycle counting were exceptional. The breakpack penalty allows for adjustment should the dynamics of cycle counting change.

In our calculations, we assume that the results are typical of the future and that the existence of a breakpack condition for an item will result in a missed count and the subsequent recounting three times as described in the cycle counting section. That recounting time is mostly composed of travel time between items then back to the miscounted item.

We represent the breakpack penalty associated with a case pack type j with the following notation:

K_j= penalty (fixed cost) incurred when opening a box of packaging type j, in order to pick single units

4.5 Material Handling Policy Considerations

We showed in the preceeding section that breakpack conditions at TP&G can cause a diverse set of problems for TP&G warehouse personnel. The problems associated with breakpack conditions incentivize TP&G warehouse managers and material handlers to minimize the opening of case packs to the greatest extent possible. This, in conjunction with the pressure on warehouse personnel to deliver a large amount of materials under tight time constraints, leads to some interesting material handling policies (sanctioned and unsanctioned by various parties). In this section, we will describe some TP&G material handling policies and procedures that have an impact on evaluating costs and how they impact the formulation of the TP&G simulation model.

4.5.1 Rule of Thumb

Rule of Thumb (RoT) is an important concept to understand within the context of TP&G and the model. RoT was developed by material handlers and other CDC personnel in order to ease the burden of material handling. RoT is essentially an algorithm used to facilitate picking. The actual rule of thumb is a percentage used for material handlers to decide how they will satisfy an order. When picking material to satisfy an order, material handlers will satisfy as much of an order as they can with whole case packs. If the remaining quantity of the order that cannot be satisfied with whole boxes is less than RoT times the case pack quantity, that remainder will not be satisfied. If the remaining quantity of the order that cannot be satisfied with whole boxes is greater than RoT times the case pack quantity, that remainder will be filled (overfilled) with a whole case-pack. The typical RoT used for all materials is 50%.

We represent the rule of thumb threshold with the following notation:

R = rule of thumb threshold for a given material (% of whole case pack)

As a tangible example, imagine a certain screw which is held in inventory in boxes of 10 screws each. If a material handler receives an order for 14 screws, the worker will pick, at a minimum, one full box of screws. This will leave a remainder of four screws to be fulfilled. This is where rule of thumb enters the picking process. If the rule of thumb is 50%, then the worker will not pick another box leaving the order short four screws. If the order was for 16, the material handler would send two whole boxes of screws, overfilling the order by four units.

RoT is not at all intuitive to an outside observer and may not make sense. Imagine if one were to order two coffee mugs from a retail website and received either none because the mugs are delivered from suppliers in cartons of eight or in another instance order four and receive a carton of eight. You would be outraged! Indeed, the internal customers of TP&G are generally outraged as well (particularly in the case of receiving no material).

Some dynamics of the regulated electric power and natural gas business are responsible for the development of the rule of thumb. We described the issues related to cycle counting and auditing when breakpack conditions exist above. The warehouse management and material handling personnel bear full responsibility for any missing items. Because of this accountability problem, CDC personnel are incentivized to minimize the number of open case packs at all times.

Another, incentive for rule of thumb is related to the actual picking of the material. The CDC personnel are generally operating at capacity to satisfy daily orders. Picking whole case packs is much easier and quicker than opening a box of washers and picking out some lesser quantity. Additionally, handling a group of small items outside of a box is somewhat unwieldy. This issue could be fixed through handling process improvement.

RoT particularly comes into play with low cost items such as fasteners which are typically small and difficult to handle individually. RoT is most often applied to spooled items such as medium density polyethylene tubing used in natural gas distribution or cable used in electricity distribution. We have covered some of the issues involved in the lower cost items. For the spooled items, the CDCs do not have a way to cut cable to custom lengths and management has decided that they will not send entire reels to satisfy orders under the RoT most often due to the desire to reduce wasted material. Orders over RoT will be satisfied with whole reels.

4.5.2 Results of RoT

The result of employing a rule of thumb as described above in the warehouse is that many orders go completely unfilled, partially filled, or overfilled. Some customers receive everything they need and more. Some customers receive none.

4.5.3 Cost of Unfulfilled Orders

We have pointed out that the use of a rule of thumb policy creates a situation where orders could potentially be partially fulfilled or unfulfilled depending on the relationship between case pack quantities, ordered quantity, and the RoT.

The existence of this situation begs the question: "What is the cost of not fulfilling orders?"

The costs associated with not fulfilling orders is wide-ranging. On the low end, it could cost essentially nothing. For example, not fulfilling a commonly used washer could be okay if the construction crews have many on hand or can easily borrow some.

On the high end, it could cost millions or tens of millions of dollars. In the case of electrical distrbution cable, for example, that cable could be the missing piece needed to complete the project, thus the project could be delayed. If the project is delayed, and third-party contracted construction crews are working, then contracts must be renegotiated, costing more money and more resources. Additionally, if the project is not closed out, it cannot be capitalized on the company's balance sheet and, therefore does not earn the regulated rate of return on those assets. Not achieving a high rate of return could cause loss of investor confidence, an ensuing selloff, and the loss of millions, or more, in market capitalization.

The cost of not fulfilling orders could be miniscule or it could be huge and will vary by item and various other conditions in the CMSC (e.g. stockpiles of the material already held by construction crews).

In the model, we will account for the cost of unfulfilled orders in the formulation but assign it a cost of zero in our analysis. We will catalog how many orders are unfulfilled (completely or partially), however.

The notation associated with unfulfilled orders is as follows:

v_j= number of orders partially or fully unfulfilled for packaging type j

Υ_j = total unfulfilled orders cost for packaging type j

F = unfulfilled order penalty

4.5.4 Cost of Overfilled Orders (Misallocated Units Cost)

We have shown how underfilling orders could impact costs in the CMSC. Overfilling orders also has an associated cost. While it is not subject to the potentially astronomical costs associated with not capitalizing assets and earning a return on those assets, overfilling orders can result in significant cost.

Work crews will continue work if they receive more material than they need (and may even be happy about the extra material). However, every unit of material is purchased for use. Sending more units to a construction site than needed incurs a penalty of the purchase cost of each additional unit.

In our analysis, we assume that all units exceeding the ordered quantity are wasted (scrapped with no recovery of monetary value).

This assumption is reasonable given observed conditions at TP&G. Current accounting regulations and policies require materials to be allocated to specific jobs. Every job has an allocated bill of materials that is ordered at the outset of work. Extra material only takes up room on trucks, so most workers throw out extra material, even if it is unused.

This cost has the potential to change greatly if, for example, management pursues developing a robust returns process that can recover these items from the field. Such a process does not currently exist, so our analysis reflects this reality.

We acknowledge that there is a chance that overfilling orders could result in an increased number of stockouts because more material is leaving the shelves in a given time period than might be expected. Material stockouts lead to unfulfilled orders and we covered those costs in the previous section. For this analysis, we will not evaluate this connection and assume that cost only comes from purchasing extra units.

The notation associated with extra units costs is:

$\Omega_j =$ total excess units cost for packaging type j

$\omega_j =$ excess units sent for packaging type j

4.6 Building the Model

In this chapter, we have outlined the considerations and some associated notation for building a total cost simulation with the total cost framework as outlined in Chapter 3 as a basis. In order to calculate the total cost for a given material and case pack type j, we only need to calculate each one of the costs for a demand set and add them together. The calculations for each of the previously mentioned variables are presented in subsequent sections. For clarity, the complete notation and assumptions are stated, even if previously mentioned.

4.7 Simulation Assumptions

The assumptions for the single-case pack deterministic demand model are:

1. Demand at the individual order level is known (e.g. from historical data).
2. Orders are placed when needed (e.g. orders do not represent an accumulation of several needed orders)
3. Case pack quantities have no impact on the time required to receive and store material

at the CDCs. (Note: receiving staff are generally not working at capacity).

4. Material handlers dedicate 100% of their paid time to handling materials.
5. Workforce size remains static throughout the evaluated time period.
6. Wages remain static throughout the evaluation period (e.g. no overtime).
7. Case packs of a given material do not vary in terms of physical properties (size, weight, durability).
8. Breakpack conditions will result in a missed inventory accountability cycle count for a given item 100% of the time.
9. All missed inventory accountability cycle counts will result in a corrective action process as outlined in Chapter 4 (see Breaking Open Packs Section)
10. Time required to pick whole case packs does not vary with time or number of boxes picked (i.e. no material handler fatigue).
11. Time required to pick individual material units does not vary with time or number of individual units picked (i.e. no material handler fatigue).
12. All units sent to customers above the ordered quantity are scrapped immediately with no recovery of value.
13. The costs of underfilling orders are subject to large variations in magnitude and are assumed to be zero in our analysis.
14. There is no purchase price variance for a given material as a function of case pack size.

4.8 Simulation Indices

$i \in \{1, \ldots, n\}$: orders received from the yards or projects

$j \in \{1, \ldots, m\}$: packaging types available from the supplier

4.9 Simulation Inputs

D_i= number of units ordered in order i

S_j= number of units in a box of packaging type j

P_j= price charged by the supplier per box of packaging type j

C_j= cost incurred in picking a *whole* box of packaging type j

K_j= penalty (fixed cost) incurred when opening a box of packaging type j, in order to pick single units

V= penalty (variable cost) incurred when picking a single unit from any opened box

4.10 Simulation Outputs

TC_j = total Cost of packaging type j

Ω_j = total excess units cost for packaging type j

ω_j = excess units sent for packaging type j

Υ_j = total unfulfilled orders cost for packaging type j

υ_j= number of orders partially or fully unfulfilled for packaging type j

z_j= whole case packs of type j used to satisfy all i

w_j= number of boxes of packaging type j opened for picking single units to satsify all i

u_j= number of individual units picked from open packages of type j to satisfy all i

4.11 Total Cost Simulation Equation

$$TC_j = z_jC_j + K_jw_j + Vu_j + \Upsilon_j + \Omega_j \tag{4.1}$$

4.12 Total Cost Sub-Components - General Case (Broken Packs Allowed)

1. Calculating Whole Case-Packs Used ($w_i s$)[1]

$$z_{ij} = \left\lfloor \frac{D_i}{S_j} \right\rfloor \tag{4.2}$$

$$z_j = \sum_{0}^{n} z_{ij} \tag{4.3}$$

2. Calculating Number of Opened Case-Packs (b_{is})

$$w_{ij} = \begin{cases} 1 & \text{if } D_i - S_j z_{ij} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{4.4}$$

$$w_j = \sum_{0}^{n} w_{ij} \tag{4.5}$$

3. Calculating Number of Individual Units Picked (u_j)

$$u_{ij} = D_i - S_j z_{ij} \tag{4.6}$$

[1]The positioning count starts from 0 in accordance with Python indexing conventions.

$$u_j = \sum_{0}^{n} u_{ij} \tag{4.7}$$

In the case where breaking packs is allowed, the costs of unfulfilled orders and overfilled orders are equal to zero because all demand is satisfied exactly. The total cost equation reduces to:

$$TC_j = z_j C_j + K_j w_j + V u_j \tag{4.8}$$

4.13 Rule of Thumb (RoT) Algorithm

Application of the Rule of Thumb Algorithm results in the elimination of breakpack conditions thus $w_j = 0 \forall i$. Because orders are not being satisfied exactly, we must account for these changes (overfilled orders, underfilled orders, etc.). Otherwise, the cost of picking whole boxes is the same as in the breakpack case.

Data: D_i, S_j, R, P_j

Result: Order Overfilled or Underfilled

if $D_i - z_{ij} S_j < RS_j$ **then**

$z_{ij} = \left\lfloor \frac{D_i}{S_j} \right\rfloor$;

$\upsilon_{ij} = 1$;

else

$z_{ij} = \left\lfloor \frac{D_i}{S_j} \right\rfloor + 1$;

$\omega_{ij} = z_{ij} S_j - D_i$;

$\Omega_{ij} = \omega_{ij} \frac{P_j}{S_j}$;

end

Algorithm 1: Rule of Thumb Picking Algorithm

4.13.1 Calculating Misallocated Unit Cost

As demonstrated, material handlers following a Rule of Thumb picking algorithm ultimately overfill or do not fully satisfy ordered quantities. Further accounting is required to calculate the impact of RoT on total handling costs.

Cost of Not Fullfilling or Partially Fulfilling Orders

As we stated earlier, the penalty for not fulfilling orders completely is represented as a simple penalty F:

$$\Upsilon_j = \sum_{i=0}^{n} v_{ij} F \tag{4.9}$$

where:

$F =$ unfulfilled order penalty

Cost of Overfilling Orders Misallocated Units Cost

$$\Omega_j = \sum_{i=0}^{n} \Omega_{ij} \tag{4.10}$$

4.13.2 Rule of Thumb "Total" Cost

$$M(s) = w_{is} c_{is} + \Omega_{is} + v_{is} F_i \tag{4.11}$$

In the RoT case, no packages are broken, and therefore, no breakpack penalty or individual unit picking costs are incurred, so the total cost equation reduces to:

$$TC_j = z_j C_j + \Upsilon_j + \Omega_j \tag{4.12}$$

4.13.3 Model Implementation in Python

The model as described has been implemented using Python 2.7 programming language and various Python-based packages including NumPy, SciPy, and Matplotlib. Python is a widely used open-source high-level open-source programming language.

We chose Python its ease of use, widespread availability of technical documentation and the adoption of Python as the de facto standard programming language within TP&G's analysis group.

In Python, we can easily display results graphically so that non-technically inclined users can see results for all evaluated sizes and use the results when making decisions.

The computational time for a simulation of even very large vectors of demand is less than one second. Therefore, we saw no reason to move the model from its Python implementation.

We have shown how we adapted our total cost framework to build a simulation model using real life circumstances within TP&G. In the next chapter, we will apply this simulation model as presented to two construction materials held in TP&G's CMSC inventory and demonstrate the results.

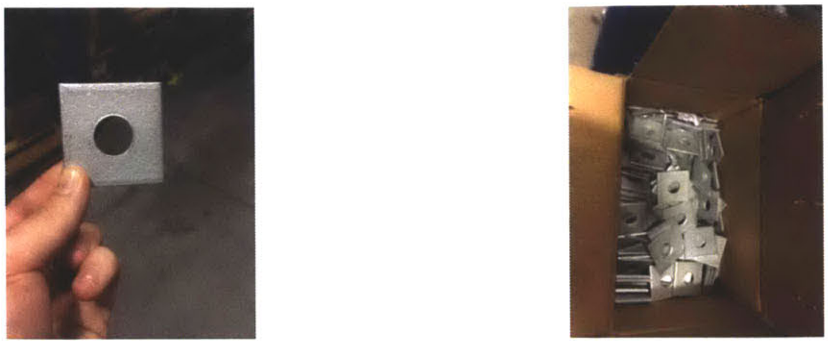
THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 5

Case Studies - The Square Washer and Electric Cable

5.1 Case Studies Introduction

Our results are best demonstrated through case studies of individual inventory items within the CMSC. The case studies will add a level of tangibility to the simulation model developed in Chapter 4 by introducing an inventory item, some basic characteristics of the item (such as price and order volume) and ultimately, assigning a dollar figure associated to the total cost of various case pack quanities and order picking policies (e.g. breakpack vs. rule of thumb).



(a) Individual Washer (b) Box of 250 Washers

Figure 5-1: Pictures of the Square Washer

5.2 The Square Washer

5.2.1 Description

The square washer as pictured in Figure 5-1 is a flat piece of metal for which the primary purpose is the spread of fastener (such as a nut) pressure across its surface to prevent damage to the materials underneath. For example, if a bolt is fitted through a hole in a telephone pole, and a nut is tightened on the other side with no washer present, the nut will press deeply into the wood, damaging it. If a square washer is there to spread out the pressure,the wood will not be damaged.

The square washer is what employees of TP&G describe as a "bread and butter item" because of its ubiquitous nature in electric power construction projects. We have chosen to highlight this item, because it is a relatively low value item, yet is one of the most ordered items from customers within the CMSC. It is representative of ordering patterns for much of the very literal "nuts and bolts" that pass through the CMSC which make up a lot of the volume of orders by number, but represent only a small amount of the monetary value of inventory items.

Square Washer Basic Information	
Order Frequency (# Orders)	3,6333
Unit Price ($)	0.26
Case-Pack Size Held in Inventory (units)	250

Table 5.1: Square Washer Basic Data

5.2.2 Square Washer Basic Data and Observations

Table 5.1 shows that the square washer is ordered with high frequency. On average, internal customers are ordering square washers from the central distribution centers ten times per day.

At $0.28 per unit, the square washer is inexpensive in the absolute and when compared to other inventory items. Currently, the case pack quantity held in inventory is a box of 250 washers. The box can be seen in the figure above.

Square Washer Handling Costs	
Whole Case-Pack Picking Costs ($/box)	
Tier 1 (<10 lbs) (<12 Washers)	$0.01
Tier 2 (10-60 lbs) (<71 Washers)	$0.03
Tier 3 (60-105 lbs) (<125 Washers)	$1.58
Tier 4 (>105 lbs)(>125 Washers)	$5.00
Breakpack Penalty ($)	$4.00
Individual Unit Picking Cost($)	$0.01

Table 5.2: Square Washer Handling Cost Data

The handling cost table clearly outlines the costs associated with each procedure or penalty for this item. The current case pack quantity falls into the category of two-person lifts.

5.2.3 Results by Case Pack Quantities

For this case study, multiple sizes were not available from the supplier, so we developed a size menu of packaging sizes of 1, 5, then multiples of 10 from 10-500 and graphed the resulting costs to generate a curve of costs as a function of case pack quantity for both the conditions of picking under rule of thumb constraints and for breakpack conditions.

In Figure 5-2 the left subplot shows how total cost varies as a function of case pack size and the breakdown of costs for a 50% rule of thumb policy into the following components:

C_j = whole box picking costs for case pack type (quantity) j

Υ_j = cost of unsatisfied orders for case pack type (quantity) j

Ω_j = cost of sending extra units for case pack type (quantity) j

The x-axis of both subplots is j (case pack type (quantity)) from the size menu. The y-axis is the cost in \$. Each plotted point represents the cost of using the corresponding case pack type.

In Figure 5-2, the cost of unsatisfied orders (Υ_j) is \$0. We chose to exclude this cost because, as we noted in Chapter 4, this cost could range from nothing to millions of dollars depending on the item. We have no way of assessing that cost for the square washer, so, we excluded its explicit calculation from this analysis.

In place of the explicit calculation of Υ_j, we calculated a customer service rate - the percentage of orders which were not completely satisfied (υ_j) out of the total number of orders n - and plotted it as a function of j. This approach allows for some accounting of the under-satisfaction of demand effects of the 50% rule of thumb policy in the absence of explicit cost calcuation.

The customer service rate subplot (right subplot in Figure 5-2 shows the resulting customer service levels for the case pack quantities evaluated.

The customer service level for a case pack quantity of one washer is 100%. This is to be expected. The rule of thumb does not come into play for a case pack quantity of one washer since all orders are 100% of the case pack quantity.

The customer service level drops off sharply after case pack quantity of 1 and for all case pack quantities greater than 30 units, the customer service level remains below 25%. It is worth reminding that the 75% of orders which are not being served includes situations ranging from customers receiving no units, to customers receiving most but not all of their ordered units. Either way, there is great room for improvement over the 50% rule of thumb policy.

The total cost graph does not include the costs of not fulfilling orders. This is done for clarity, because, as we stated before, the cost of not fulfilling orders is not clear and could be wide-ranging and, thus, currently does not provide much useful information.

The total cost graph shows that total cost increases steadily with case pack size, and that most of that cost is composed of extra units cost. Figure 5-3 shows the plot of the number of extra units sent (ω_j) by case pak quantity in the left subplot and the total associated cost of those extra units in the right subplot.

One might be tempted to conclude that extra units costs dominate in this case. While that may be displayed, this is only part of the story. These results give a skewed view because some orders are not being served at all. Therefore, no handling cost is incurred to serve that order. This lack of accounting for picking costs is exacrbated as case pack quantities increase. As they increase, fewer orders or remainders of orders meet the 50% threshold, and the ones that do, are overserved with even more units than they previously were. For example, if an order exists for 200 units, that order will be completely served every time with boxes of 200. If the $S_j = 210$ then the order will be overserved by 10 units. If $S_j = 400$ units, that order will be overserved by 200 units. At $S_j > 400$ units, the order will not be served. Thus, the order accrues a massive overserving cost, until it is not served at all, and thus incurs no handling cost, as we increase the evaluated case pack quantity.

Figure 5-4 shows the total number of units ordered but not fulfilled as a function of case pack quantities and illustrates the dynamic highlighted above. As the case pack quantities increase, the number of unsatisfied units skyrockets.

The only hard conclusion that we can draw about the 50% rule of thumb policy is that for the washer, the majority of orders are not completely satisfied for the majority of case pack

Square Washer Cost Comparison - 50% Rule of Thumb			
Case Pack Quantity (# units)	250 (Current)	10 (Lowest)	50 (Next Best)
Total Cost ($)	12,762	544	712
Handling Cost ($)	4,991	244	136
Extra Units Cost ($)	7,659	300	556
Customer Service Rate	18.1%	33.3%	21.9%

Table 5.3: Square Washer - Case Pack Cost Comparison under 50% RoT

quantities in the presented menu.

This result in retrospect, may seem obvious, but it was only through application of the TP&G total cost simulation that we were able to dissect the underlying dynamics of the rule of thumb policy and its impact on costs.

5.2.4 Comparison of Optimal Case-Pack Quantity and Current Case-Pack Quantity Under Current Policies

Even though we have shown that the current practice of 50% rule of thumb is not optimal for the washer, we have still shown that choice of case pack quantity has some impact on the rule of thumb policy.

The cost-minimizing case pack quantity for the square washer under the 50%rule of thumb policy and the given demand set, is 10 units. Table 5.3 compares the components of cost between the current case pack quantity and the lowest-cost quantity of 10 units.

Even with no changes in policy, just carrying a case pack quantity of 10 washers would improve all measures of performance for the square washer by a significant margin.

It is important to emphasize, once again, that our analysis does not include any cost penalty for a vendor changing an offered packaging size, and it is reasonable to believe that case pack quantities of 10 may result in significant extra costs. Taking this into account, we also compared the next best case pack quantity on a cost basis. Table 5.3 also illustrates the results for a case pack quantity of 50 units.

Square Washer Cost Comparison - Breakpack Policy		
Case Pack Quantity (# units)	250 (Current)	50 (Lowest)
Total Cost ($)	3,811	315
Handling Cost ($)	3,811	315
Extra Units Cost ($)	0	0
Customer Service Rate	100%	100%

Table 5.4: Square Washer - Case Pack Cost Comparison under Breakpack Policy

A 50 unit case pack quantity would improve cost and customer service level by a similar margin to the cost-minimizing 10 unit case pack, if a 10 unit case pack results in significant extra costs.

5.2.5 Evaluation of Alternate Policy - Breakpack

While TP&G material handlers do currently employ a rule of thumb policy, a breakpack policy is touted by TP&G warehouse personnel as the other option for a picking policy for inventory items - in this case the square washer. Under the breakpack policy, all orders are fulfilled as ordered and material handlers open packages to do so.

Figure 5-5 shows the total cost graph and fulfillment rates for a breakpack policy. In this case, the only cost is handling cost and the fulfillment rate is 100% across the menu of sizes. This is a situation with which TP&G internal customers would be very pleased.

Table 5.4 demonstrates the effects on cost of adopting a policy of fulfilling all orders both for current case pack quantities and for the cost minimizing case pack from the menu of sizes.

The left column shows the cost components for the current case pack quantity held in inventory if a breakpack policy is adopted as outlined. The figure also shows the percentage improvement over the rule of thumb policy.

The right column of the figure shows the cost components for the cost-minimizing case pack quantity, the percentage improvement over the current case pack under the current rule of thumb policy (left percentage), and the percentage improvement over the current case pack quantity under a breakpack policy (right percentage).

Even if the current case pack quantity is maintained, vast improvements can be made to all aspects of cost over the current rule of thumb policy. Most notable is the fact that extra unit costs disappear completely and the customer service level is 100%. As stated earlier, there is some cost associated with not fulfilling orders that we are not accounting for in these figures. If a break pack 100% fulfillment policy is adapted, these costs would be non-existent.

The important conclusions to draw from Figure **??** are:

1. Even for the current case pack quantity of 250, handling cost is reduced because not many orders are being satisfied with whole boxes, which are heavy (and therefore expensive to handle). This effect outweighs the fact that material handlers are fulfilling more orders.

2. Costs fluctuate greatly as a function of case pack quantity and choosing one "correctly" can result in significant savings for TP&G above and beyond just what can be achieved from a policy change alone.

5.2.6 Conclusions about policies and the Square Washer

It is clear from this analysis that TP&G's current rule of thumb policies result in significant misallocation of resources. Many extra units are sent to customers who did not order them, while other customers receive only partial amounts of the quantity of washers they ordered, or nothing at all. Regardless of whether or not case pack quantities carried in inventory will be changed, the optimal policy is to satisfy all demand whether it is through a policy of fulfilling all orders as ordered, or relaxing that constraint slightly to allow for some overfilling of orders.

Even changing material handling policies alone will result in significant cost savings in the CMSC with regards to the square washer.

5.2.7 Conclusions about Case-Pack Quantities for the Square Washer

It is clear from our analysis that great savings can be achcived from adopting a new set of policies. There are, however, also significant savings to be gained from pairing those policy changes with an optimization of square washer case pack quantities.

Optimal and near optimal case pack quantities for the washer are ten and fifty, which are factors of demand. This is a generalizable result of this analysis from which any company that fulfills orders could benefit - optimal case pack quantities are factors of the demand. In the case of the washer, orders tend to be in multiples of 10, 50, or 100. Orders which are multiples of 100 can be satisfied with whole case packs of 50 while still allowing for orders of 100 or less to be satisfied with a whole case pack and some extra. Likewise, multiples of 100 and 50 can be satisfied with whole case packs of 10 while still allowing for orders that are less than 50 to be satisfied usually with whole case packs.

5.3 Electric Cable

5.3.1 Electric Cable Description

Electric Cable is a core product for TP&G. Indeed, on the electric side of the business, cable is the most important item. It is through cables such as this one that electricity is ultimately transmitted and distributed. The motivation for choosing to use cable for a case study is its inherent importance to the business. It also illustrates the dynamics for all reeled or spooled inventory items (none of which TP&G has the ability to send any less than entire reels or spools). Both the gas and electric sides of the business maintain vast assortments of reeled gas piping or electrical cable that are core to any infrastructure construction project.

Electric Cable Basic Information	
Order Frequency (# Orders)	29
Unit Price ($/ft)	54.38
Case-Pack Size Held in Inventory (ft)	900

Table 5.5: Electric Cable Basic Data

5.3.2 Basic Electric Cable Data

Table 5.5 shows that when compared to the square washer, the order frequency is quite a bit lower, and the unit cost is quite a bit higher. In this case, the cable presented, like many cables used in electric power transmission and distribution, is made mostly of copper (a relatively expensive commodity - approximately $3 per pound at the time of writing) and manufactured to a very narrow specification.

Electric Cable Handling Costs	
Whole Reel Picking Cost (All Sizes)	$5.00
Breakpack Penalty ($)	N/A
Individual Unit Picking Cost($)	N/A

Table 5.6: Electric Cable Handling Cost Data

As is the case with the basic data regarding electric cable, the handling cost data presented in Table 5.6 differs significantly from that of the square washer. In the case of the cable, there is only one handling cost - that of picking an entire reel. TP&G does not have the ability to send out partial reels of cable or sections of cable because TP&G does not currently have the required tools or supporting systems in place to do so. Currently customers either get a whole reel of cable for orders over 450 ft, or they receive no cable for orders under 450 ft. Also, any cable reel of almost any size would require a fork-lift to move. Any amount of this cable is extremely large and heavy and can only be moved one reel at a time.

The idea of only having a system of sending an entire reel or nothing to fulfill all orders may seem preposterous to the reader and the reader may think this system must obviously be improved, but we suggest that implementing a successful system otherwise would be extremely capital and labor intensive given the difficulty of handling cable like this both in the warehouse and at the job site. For example, implementing a system to cut lengths of cable in the warehouse may seem like an easy solution, until one thinks of trying to handle say, a 600 ft. section of loose copper cable.

In this case, our analysis will help TP&G's management gain more specific insight into what is, anecdotally, a problem in the organization.

5.3.3 Results by Reel Size

In the same way that we charted the total cost and composition of total cost for the square washer by case pack size, we have analyzed the total cost and components for a set of reel sizes ranging from 100 ft to 1600 ft in increments of 100.

Figure 5-7 shows the total cost, components and service levels for the set of reel sizes. Note that handling costs are an extremely small part of the costs. On the scale of the graph, they almost cannot be seen. It is extra unit purchasing costs which dominate the total cost.

This result intuitively makes sense. The maximum cost for handling these 29 orders, assuming all receive an entire reel is \$5 x 29 = \$145 . And if we consider that in the current state that someone who orders 451 ft of cable would receive excess of 449 ft at a total cost of 449 ft x \$54.38 = \$24,417, the disproportionate impact of extra unit costs when compared to handling costs makes sense.

Figure 5-8 shows the number of extra units sent to job sites and the associated costs for the given demand set in detail.

Figure 5-9 shows the number of unfulfilled orders by reel size. Intuitively, as the reel size increases, the number of orders that do not meet the 50% rule of thumb also increases, so the number of unfulfilled units increases.

Unlike in the case of the square washer, however, the cost of not fulfilling these orders is likely to be very high. Unlike the square washer, work crews may not have some extra

Electric Cable Cost Comparison - 50% Rule of Thumb		
Case Pack Quantity (ft.)	900 (Current)	100 (Lowest)
Total Cost ($)	109,335	18,544
Handling Cost ($)	140	1360
Extra Units Cost ($)	109,195	17,184
Customer Service Rate	37.9%	44.9%

Table 5.7: Electric Cable - Case Pack Cost Comparison under 50% RoT

highly engineered cable in their trucks, and this cable is not the type of material that can be purchased at a local hardware store in a pinch. Therefore, work is most certainly halted until work crews can acquire cable for the job.

5.3.4 Comparison of Optimal Reel Size and Current Reel Size Under Current Policies

The optimal reel size for this demand set and size menu is 100 ft.

Table 5.7 shows the results comparing a 100 ft. reel size to the current 900 ft reel size.

Adopting a reel size of 100 ft. would result in a sharp increase in handling cost. This is to be expected because more orders will be served and with more reels. As we stated earlier, handling a 100 ft reel does not materially differ from handling a 900 ft reel.

The extra units cost, however drops significantly and the customer service rate increases as well.

5.3.5 Conclusions about Current Reel Sizes for Electric Cable

Again, as in the case of the washer, we observe that the optimal case pack quantity under current TP&G policies is a factor of the modes of demand. In this case, customers tend to order cable in multiples of 100. With a 100 ft reel size, any multiple of 100 can be easily satisfied.

There is no use at this point in comparing break pack models for the cable because the costs involved in instituting such a system are very unclear. However, this analysis should spur TP&G management to consider entering into negotiations with suppliers to reduce reel size, and begin an investigation into the ways in which cable can be delivered as ordered.

5.4 Case Study Conclusions

In both case studies, we demonstrated that under the current 50% rule of thumb policy, the costs of misallocating units (both in overserving demand, and in not fulfilling orders) dominate the total costs of serving demand in the CMSC.

We offered the alternative policy of breaking packs to serve demand exactly as a better policy for any case pack quantity.

We also showed that significant cost savings can be achieved in conjunction with or by ensuring that packaging sizes are factors of modes of demand (e.g. if customers order in mutliples of 100, case pack quantities of 10,50, or 100 are likely to be the optimal sizes).

These results are consistent across items in TP&G's supply chain. These items were highlighted because they are representative of the two most anecdotally troublesome categories of materials for TP&G management and employees. From an analytical perspective, they also represent interesting items to evaluate the tradeoffs between labor costs and the costs of materials.

The results of these case studies were presented to TP&G's management and sparked further investigation into how recommended changes can be implemented within the CMSC.

The results presented in this chapter were not meant to condone policies currently implemented within TP&G. Rather, we used our novel handling cost accounting method to describe, in a cost based manner, current operations within TP&G.

In Chapter 6, we will move from a descriptive model to a prescriptive model in which we present a method for determining what is optimal for all organizations which are structured in a similar way to TP&G.

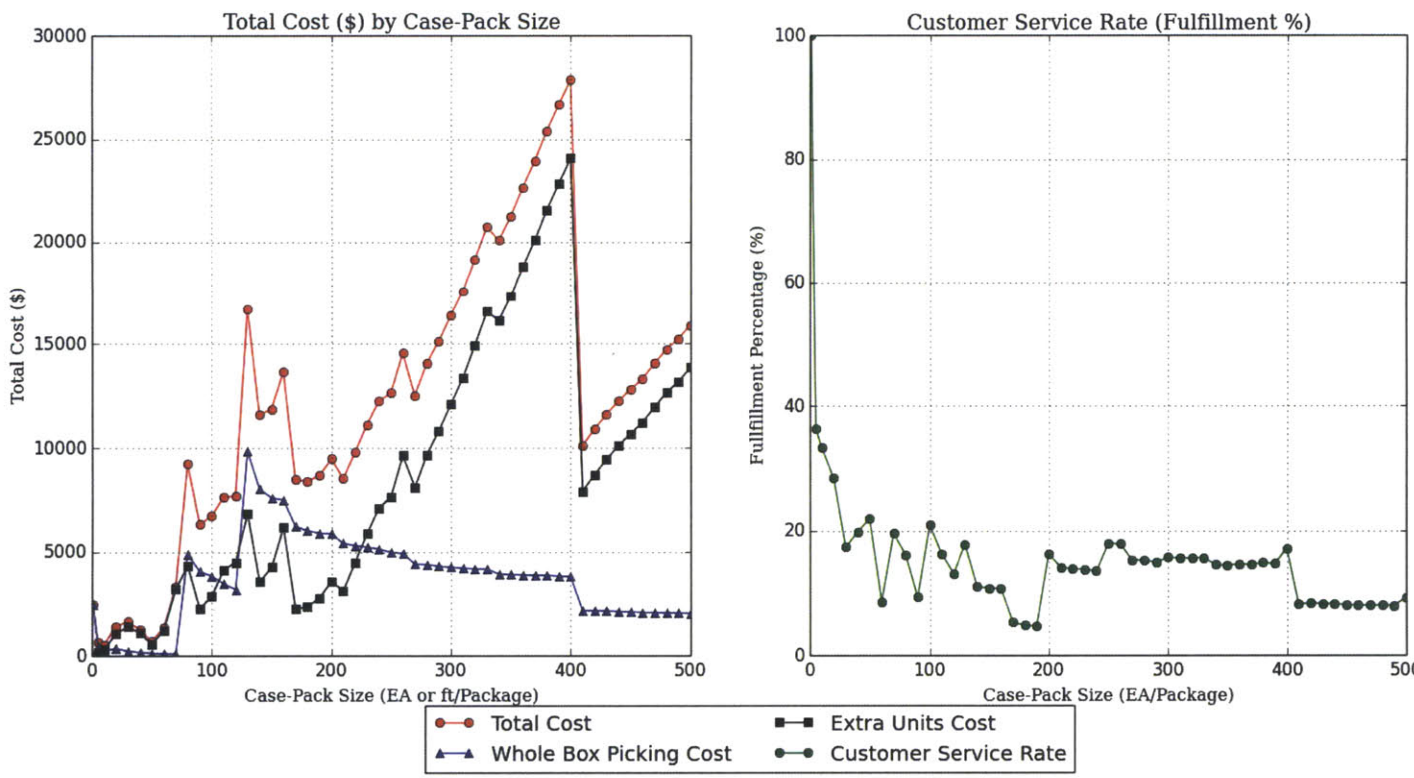


Figure 5-2: Rule of Thumb: Washer Total Cost and Customer Service Level

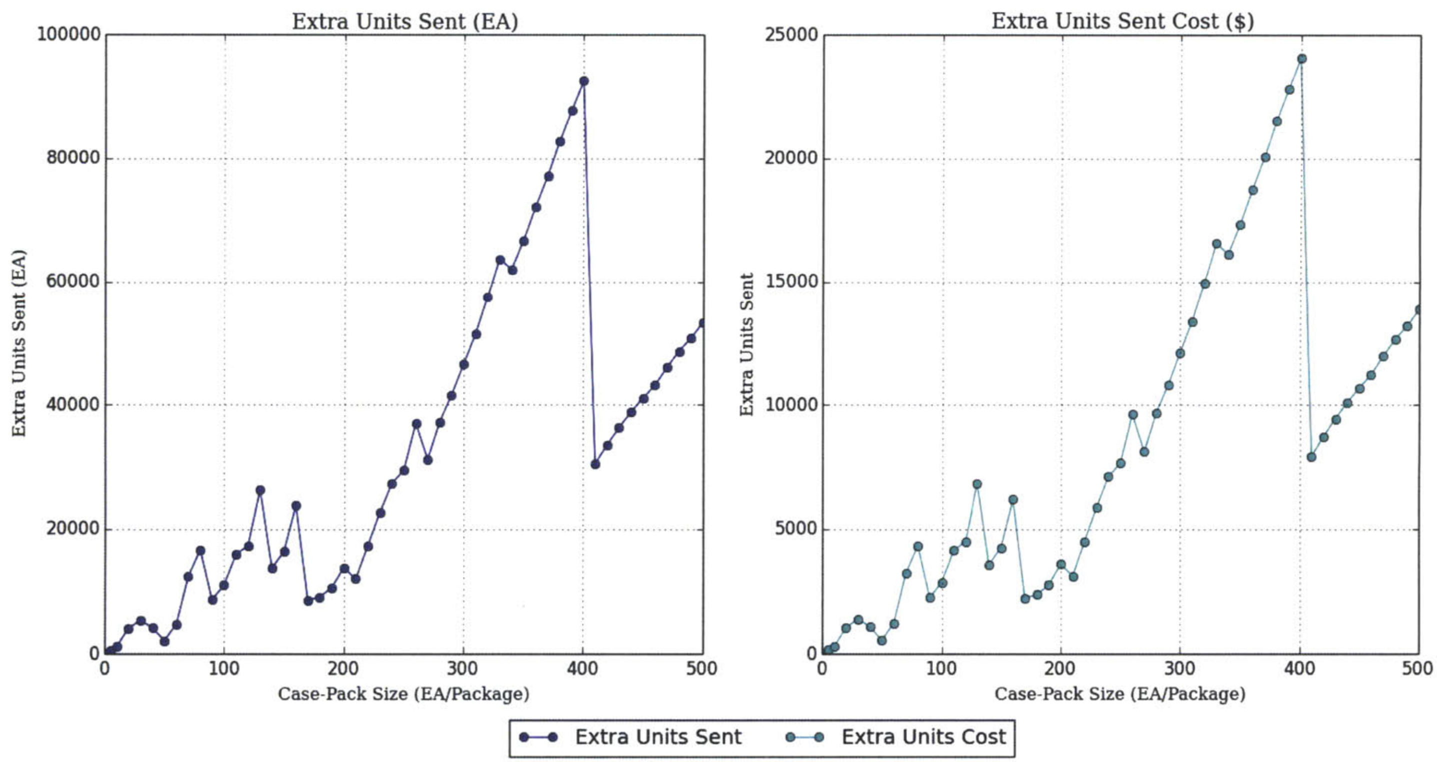


Figure 5-3: Rule of Thumb: Extra Units Sent and Associated Cost

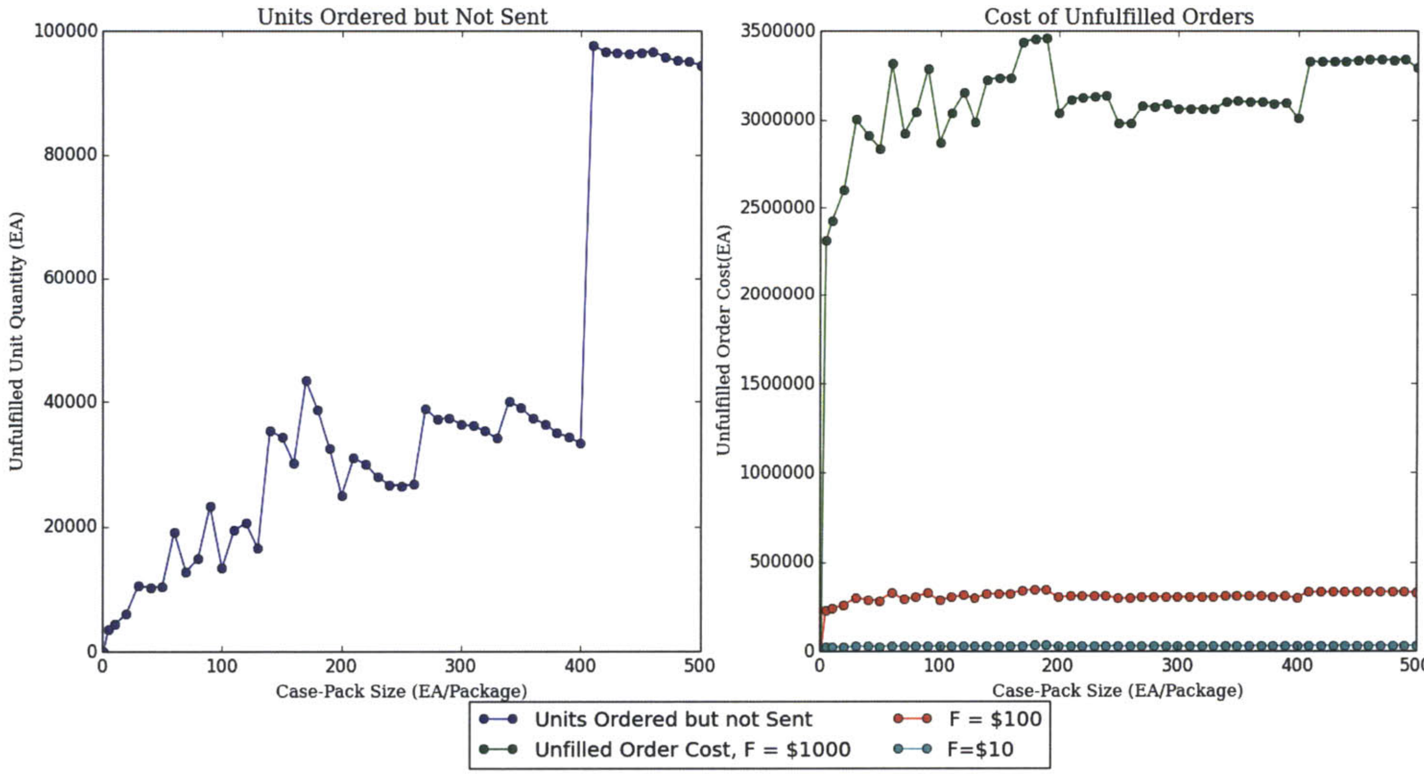


Figure 5-4: Rule of Thumb: Unfulfilled Units and Potential Costs

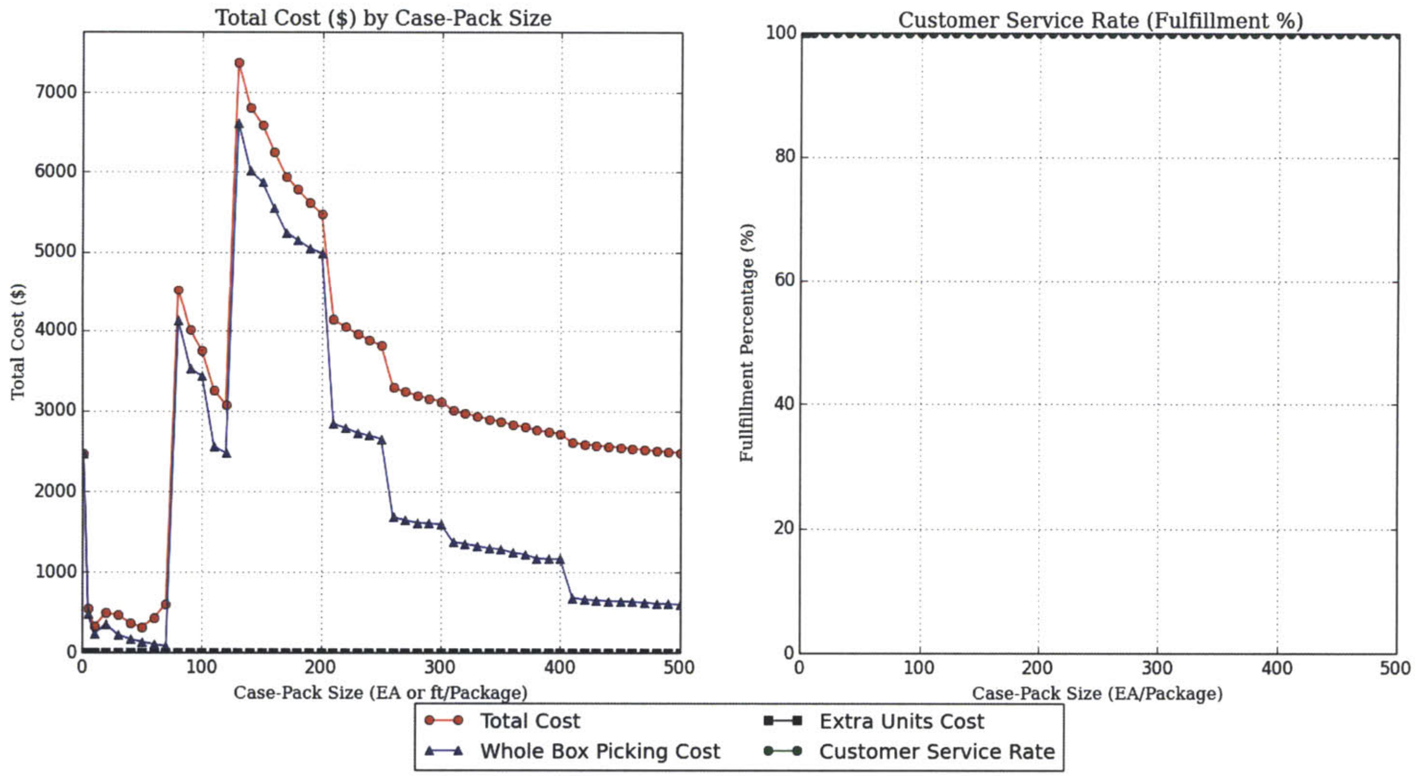


Figure 5-5: Total Cost Graph for "Breakpack" Fullfillment Policy

Figure 5-6: Representative Picture of Electric Cable Reel

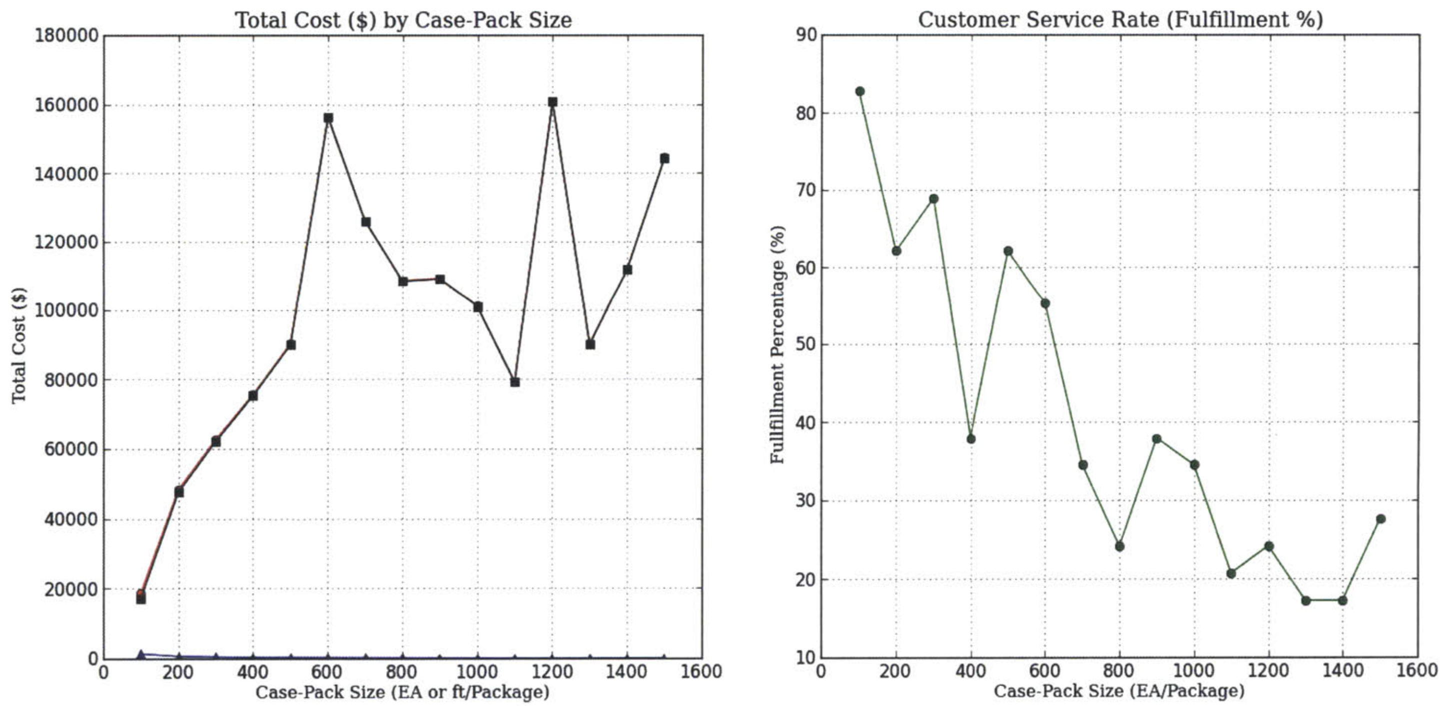


Figure 5-7: Cable Total Cost and Customer Service Levels

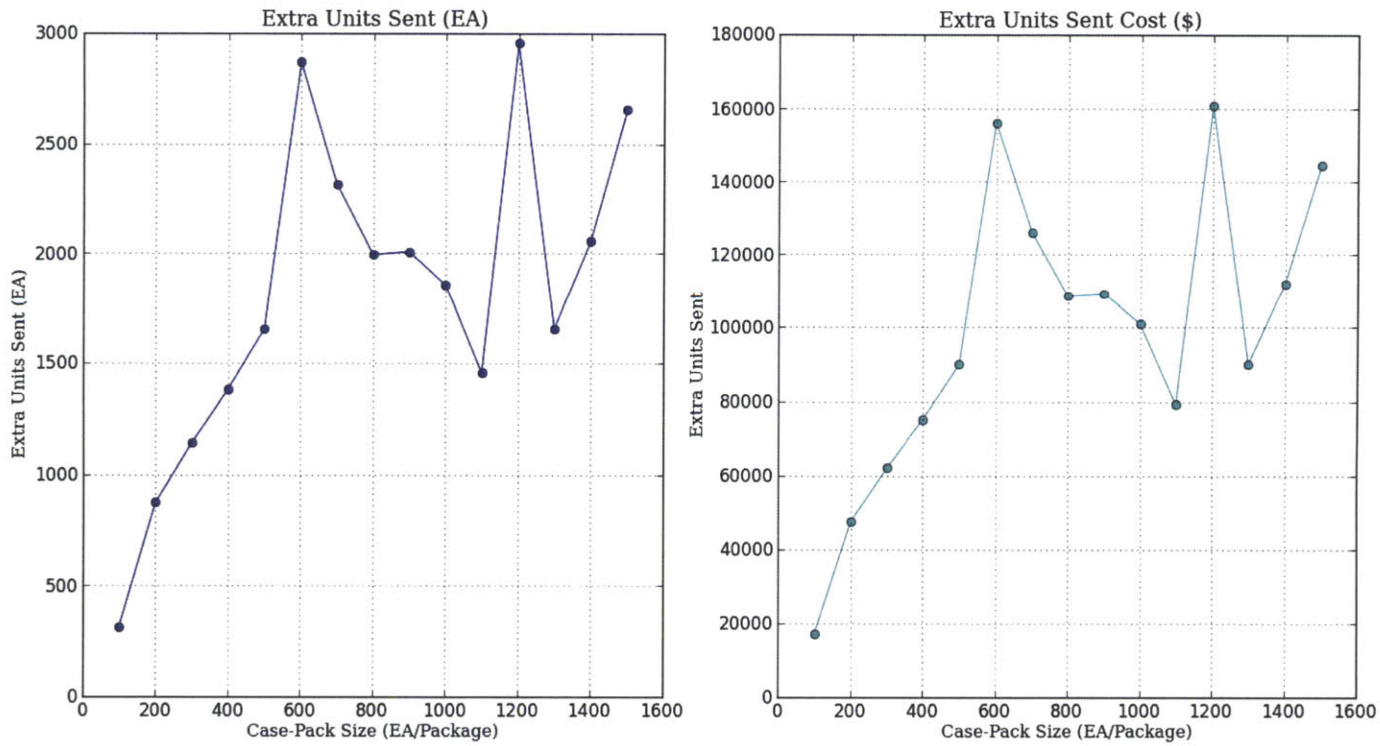


Figure 5-8: Electric Cable Extra Units (ft) Sent and Associated Cost

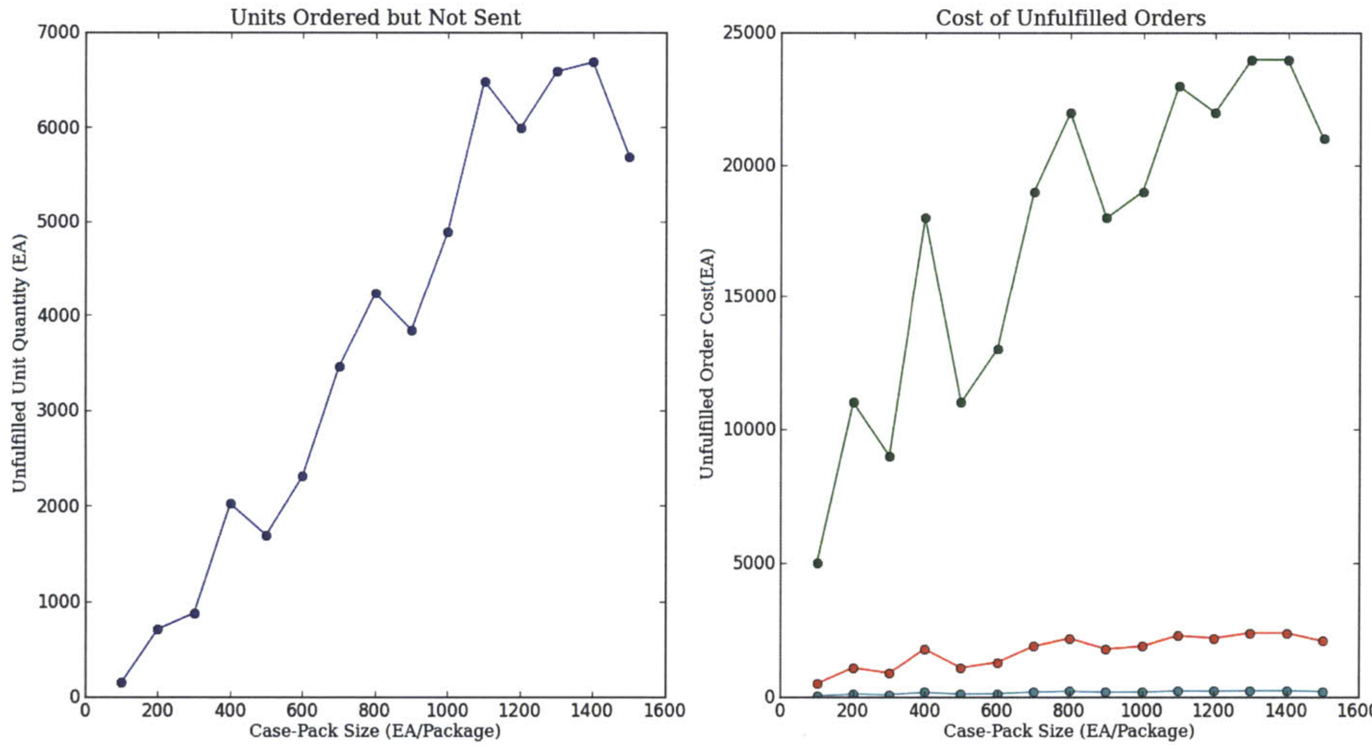


Figure 5-9: Electric Cable Unfulfilled Units and Potential Costs

Chapter 6

Optimization Models

We present an integer programming model that balances procurement costs and warehouse picking costs, in order to satisfy a vector of given orders for one SKU. It decides how many case packs of each packaging type to order from the supplier.

6.1 Indices

$i \in \{1, \dots, n\}$: orders received from the yards or projects

$j \in \{1, \dots, m\}$: packaging types available from the supplier

6.2 Parameters

$D_i =$ number of units ordered in order i

$S_j =$ number of units in a case pack of packaging type j

$P_j =$ price charged by the supplier per case pack of packaging type j

$C_j =$ cost incurred in picking a *whole* case pack of packaging type j

K_j= penalty (fixed cost) incurred when opening a case pack of packaging type j, in order to pick single units

V= penalty (variable cost) incurred when picking a single unit from any opened case pack

We make the following assumption on the cost parameters.

Assumption 1: Assume that for each packaging type j, $C_j < K_j + S_j V$.

Assumption 1 states that it is always more convenient to pick a whole case pack rather than opening it and picking each single unit from it.

6.3 Decision Variables

q_{ij}= number of units for order i satisfied from case packs of packaging type j

z_{ij}= number of *whole* case packs of packaging type j used to satisfy order i

w_j= number of case packs of packaging type j opened for picking single units

Note that the total number of case packs of packaging type j ordered from the supplier is $(w_j + \sum_{i=1}^{n} z_{ij})$. Namely, the number of case packs assigned to be opened to pick single units from, plus total number of whole case packs assigned to satisfy any order i.

6.4 Objective Function

The objective function is the total cost of purchasing and picking. It is composed by four terms: the purchasing cost, the cost of using *whole* case packs to serve the orders, the cost of opening case packs for picking and the cost of picking units from the opened case packs.

The mathematical formulation is,

$$\underbrace{\sum_{j=1}^{m}\left(w_j+\sum_{i=1}^{n} z_{ij}\right)P_j+}_{\text{Purchasing Cost}}\ \underbrace{\sum_{j=1}^{m}\sum_{i=1}^{n} z_{ij}C_j}_{\text{Whole case packs Cost}}\ +\ \underbrace{\sum_{j=1}^{m} w_jK_j}_{\text{Open case packs Fixed Cost}}\ \underbrace{+\sum_{j=1}^{m}\sum_{i=1}^{n} n(q_{ij}-z_{ij}S_j)V}_{\text{Picking Single Units Cost}}$$

6.5 Constraints

1. For each order i, the total number of units assigned to it must cover the units ordered:

$$\sum_{j=1}^{m} q_{ij} \geq D_i \quad \forall i \in \{1,\dots,n\}$$

2. Definition of the variable z_{ij} as the number of *whole* case packs of packaging type j used to satisfy order i:

$$z_{ij}S_j \leq q_{ij} \leq (z_{ij}+1)S_j \quad \forall i \in \{1,\dots,n\}, j \in \{1,\dots,m\}$$

3. Definition of the variable w_j as the number of case packs of packaging type j opened for picking single units:

$$\sum_{i=1}^{n}(q_{ij}-z_{ij}S_j) \leq w_jS_j \quad \forall j \in \{1,\dots,m\}$$

4. Integer and non-negative variables:

$$z_{ij}, w_j \in \mathbb{N}^+ \quad \forall i \in \{1,\dots,n\}, j \in \{1,\dots,m\}$$

$$q_{ij} \geq 0 \quad \forall i \in \{1,\dots,n\}, j \in \{1,\dots,m\}$$

6.6 Problem formulation

$$
\begin{aligned}
\min \quad & \sum_{j=1}^{m}\sum_{i=1}^{n} z_{ij}(P_j + C_j) + \sum_{j=1}^{m} w_j(P_j + K_j) + \sum_{j=1}^{m}\sum_{i=1}^{n}(q_{ij} - z_{ij}S_j)V \\
\text{s.}t. \quad & \sum_{j=1}^{m} q_{ij} \geq D_i \quad \forall i \in \{1, \ldots, n\} \\
& q_{ij} \leq (z_{ij} + 1)S_j \quad \forall i \in \{1, \ldots, n\}, j \in \{1, \ldots, m\} \\
& q_{ij} \geq z_{ij}S_j \quad \forall i \in \{1, \ldots, n\}, j \in \{1, \ldots, m\} \\
& \sum_{i=1}^{n}(q_{ij} - z_{ij}S_j) \leq w_jS_j \quad \forall j \in \{1, \ldots, m\} \\
& z_{ij}, w_j \in \mathbb{N}^+ \quad \forall i \in \{1, \ldots, n\}, j \in \{1, \ldots, m\} \\
& q_{ij} \geq 0 \quad \forall i \in \{1, \ldots, n\}, j \in \{1, \ldots, m\}
\end{aligned}
$$

6.7 Choosing One Case Pack Size Only

If we restrict ourselves to choose one case pack size only, we could add binary variables as indicators of whether each case pack size has been chosen, and restrict its sum to be at most one. Alternatively, if for each case pack size we can compute the total cost of using only that case pack size efficiently, then we can directly choose the case pack size that generates the smallest total cost.

Note that for a given case pack size S, we are interested in solving the following integer program, which gives the total cost of using only that case pack size. This is essentially the same program that in the previous section restricted to only one case pack size S, therefore we have dropped the dependency in the case pack size type j.

$$
\begin{aligned}
\min \quad & \sum_{i=1}^{n} z_i(P+C) + w(P+K) + \sum_{i=1}^{n}(q_i - z_iS)V \\
\text{s.}t. \quad & q_i \geq D_i \quad \forall i \in \{1,\ldots,n\} \\
& q_i \leq (z_i+1)S \quad \forall i \in \{1,\ldots,n\} \\
& q_i \geq z_iS \quad \forall i \in \{1,\ldots,n\} \\
& \sum_{i=1}^{n}(q_i - z_iS) \leq wS \\
& z_i, w \in \mathbb{N}^+ \quad \forall i \in \{1,\ldots,n\} \\
& q_i \geq 0 \quad \forall i \in \{1,\ldots,n\}.
\end{aligned}
$$

For any given case pack size S, let us define the remainder orders as follows,

$$
\tilde{D}_i \equiv D_i - \left\lfloor \frac{D_i}{S} \right\rfloor \quad \forall i \in \{1,\ldots,n\},
$$

where by definition we have $\tilde{D}_i \in \{0,1,\ldots,S-1\}$.

It turns out that we can solve the integer program in this section efficiently, as shown in the following proposition.

Proposition 1 *For any given case pack size S, assume without loss of generality that the remainder orders are numbered such that $\tilde{D}_1 \leq \tilde{D}_2 \leq \ldots \leq \tilde{D}_n$. Then, there exists an optimal threshold policy to serve the remainder orders at the distribution center, where*

- *If the remainder order $\tilde{D}_i$ is larger than the threshold $\bar{d}$, then use a whole case pack.*
- *Otherwise pick the remainder order $\tilde{D}_i$ from an open case pack.*

Where the threshold $\bar{d}$ is one of the remainder demands $\tilde{D}_i$.

Proof: First, given a case pack size S, from Assumption 1 it follows that for each order D_i, $i \in \{1,\ldots,n\}$, there is nothing better that we can do with the first $\lfloor \frac{D_i}{S} \rfloor$ units of the order than serving them by picking whole case packs. Then, any optimal solution would have a cost of at least

$$\sum_{i=1}^{n}(P+C)\left\lfloor\frac{D_i}{S}\right\rfloor. \tag{6.1}$$

Hence, solving the problem in this section reduces to deciding how to serve the remainder units of the orders that are not considered in the previous equation.

Second, the problem of deciding how to serve the remainders $\tilde{D}_i$ can be posed in the following terms. Let Δ be the set of all the remainders of the orders, namely $\Delta = \{\tilde{D}_1, \tilde{D}_2, \ldots, \tilde{D}_n\}$. Let $\Omega \in 2^{\Delta}$ be the set of remainders that are served from open case packs. Therefore $\Delta \setminus \Omega$ is the set of remainders that are served using whole case packs. Note that the cost incurred when choosing a set $\Omega \in 2^{\Delta}$ is

$$f(\Omega) = (P+C)|\Delta \setminus \Omega| + (P+K)\left\lceil\frac{\sum_{\tilde{D}_i\in\Omega}\tilde{D}_i}{S}\right\rceil + \left(\sum_{\tilde{D}_i\in\Omega}\tilde{D}_i\right)V. \tag{6.2}$$

Specifically, the first term corresponds to the cost of using whole case packs to satisfy the remainders. Because by definition $\tilde{D}_i < S$ for each $i \in \{1, \ldots, n\}$, it follows that this cost is only the cost of buying and picking a whole case pack $(P + C)$ times the number of remainders served with whole case packs, namely the cardinality of the set $\Delta \setminus \Omega$. In the second term, all the remainders that are served from open case packs are pooled together, and the total number of open case packs needed to serve them is computed considering that the orders to the supplier must be an integer number of case packs (therefore rounding up the fraction obtained when dividing by the case pack size S). Finally, the last terms add up the total number of units that need to be individually picked, and compute the total cost of individual picking by multiplying by the unit picking cost V.

Hence, the total cost of using case pack size S only can be computed by

$$(P+C)\sum_{i=1}^{n}\left\lfloor\frac{D_i}{S}\right\rfloor + \min_{\Omega\in 2^{\Delta}} f(\Omega). \tag{6.3}$$

Where the first term follows from equation (6.1) in observation (i). Namely, the cost of the serving the first $\lfloor \frac{D_i}{S} \rfloor$ units of order D_i cannot be smaller than the first term. The second term is the minimum cost of serving the remainders, where function $f(\Omega)$ is defined in equation (6.2).

It turns out that $\min_{\Omega \in 2^{\Delta}} f(\Omega)$ can be computed efficiently. Specifically, from Lemma 1 below and the assumption that $\tilde{D}_1 \leq \tilde{D}_2 \leq \ldots \leq \tilde{D}_n$ it follows that the minimizer of $f(\Omega)$ must be of the form $\Omega_k = \{\tilde{D}_1, \ldots, \tilde{D}_k\}$, for some $k \in \{1, \ldots, n\}$. It follows that we can directly try all possible values of k and keep the the best to solve this problem efficiently. Moreover, the structure of the optimal solution is a threshold policy as described in the statement of the proposition. ■

It follows that for each case pack size we can compute the total induced cost efficiently. Hence, we can directly select the case pack size that generates the smallest total cost and solve the problem of choosing only one case pack size.

Lemma 1 *Any minimizer $\Omega \in 2^{\Delta}$ of $f(\Omega)$ must be such that, any $\tilde{D}_i \in \Omega$, $\tilde{D}_j \notin \Omega$, must satisfy $\tilde{D}_i \leq \tilde{D}_j$.*

Proof: Assume for a contradiction that $\Omega \in 2^{\Delta}$ minimizes $f(\Omega)$ and there exists indexes i, j such that $\tilde{D}_i \in \Omega$, $\tilde{D}_j \notin \Omega$, and $\tilde{D}_i > \tilde{D}_j$. Let $\Omega' \in 2^{\Delta}$ be such that $\Omega' = \Omega' \setminus \{\tilde{D}_i\} \cup \tilde{D}_j$. Namely, Ω' is the set that induces a solution almost equal to the one induced by Ω, except that it interchanges $\tilde{D}_i$ with $\tilde{D}_j$. Then,

$$
\begin{aligned}
f(\Omega') &= (P+C)|\Delta \setminus \Omega'| + (P+K)\left\lceil \frac{\sum_{\tilde{D}_k \in \Omega'} \tilde{D}_k}{S} \right\rceil + \left(\sum_{\tilde{D}_k \in \Omega'} \tilde{D}_k \right) V \\
&= (P+C)|\Delta \setminus \Omega| + (P+K)\left\lceil \frac{\sum_{\tilde{D}_k \in \Omega} \tilde{D}_k - \underbrace{(\tilde{D}_i - \tilde{D}_j)}_{>0}}{S} \right\rceil + \left(\sum_{\tilde{D}_k \in \Omega} \tilde{D}_k \right) V - \underbrace{(\tilde{D}_i - \tilde{D}_j)}_{>0} V \\
&< (P+C)|\Delta \setminus \Omega| + (P+K)\left\lceil \frac{\sum_{\tilde{D}_k \in \Omega} \tilde{D}_k}{S} \right\rceil + \left(\sum_{\tilde{D}_k \in \Omega} \tilde{D}_k \right) V \\
&= f(\Omega).
\end{aligned}
$$

This contradicts $\Omega \in 2^{\Delta}$ being the minimizer of $f(\Omega)$. ■

6.8 Incorporating Demand Uncertainty: One Case Pack Size Only

In this section we assume that the order sizes are uncertain, and that they must be satisfied sequentially. More precisely, we assume that in each stage one order arrives and must be satisfied, and the size of the order follows a known discrete distribution, where $D = d_i$ with probability p_i, $i \in \{1, \ldots, n\}$. We are interested in computing the long run average expected cost induced by using case packs of a given case pack size S to satisfy the orders. If we can compute it efficiently, then we can simply select the case pack size that induces the smallest long run average expected cost to solve the problem.

We repeat here the parameters definition, and the assumptions we made about them. They are essentially the same as in Section 6.

6.9 Parameters

$S=$ number of units in a case pack of the packaging type under consideration

$P=$ price charged by the supplier per case pack of packaging type S

$C=$ cost incurred in picking a *whole* case pack of packaging type S

$K=$ penalty (fixed cost) incurred when opening a case pack of packaging type S, in order to pick single units

$V=$ penalty (variable cost) incurred when picking a single unit from any opened case pack

6.10 Random Variables

$D_t=$ number of units ordered in stage t, $t \in \{1, \ldots\}$. D_t are i.i.d. and $D_t = d_i$ with probability p_i, $i \in \{1, \ldots, n\}$.

Assumption 1: Assume that for any packaging type S, $P + C < P + K + S \cdot V$.

Assumption 1 states that it is always more convenient to pick a whole case pack, rather than opening it and picking each single unit from it. We make the following additional assumption.

Assumption 2: Assume that for any packaging type S, $P + K + S \cdot V < (P + C)S$.

Assumption 2 states that it is always more convenient to open a case pack and pick each single unit from it, rather than satisfying S units of demand, each one with a whole case pack.

As in the previous section, in order to solve this program efficiently we make the following observation.

(i) Given a case pack size S, from Assumption 1 it follows that for each order D_t, $t \in \{1, \ldots\}$, there is nothing better that we can do with the first $\lfloor \frac{D_t}{S} \rfloor$ units of the order than serving them by picking whole case packs. Then, any optimal solution would have a long run average expected cost of at least

$$\sum_{i=1}^{n}(P+C)p_i\left\lfloor\frac{d_i}{S}\right\rfloor. \tag{6.4}$$

Hence, solving the problem in this section reduces to deciding what how to serve the remainder units of the orders that are not considered in the previous equation.

Therefore, define the following modified orders (remainders)

$$\tilde{D}_t \equiv D_t - \left\lfloor\frac{D_t}{S}\right\rfloor \quad \forall t \in \{1,\ldots\}.$$

Where by definition we have $\tilde{D}_t \in \{0,1,\ldots,S-1\}$. Note that $\tilde{D}_t$ are i.i.d. and follow the following discrete distribution, $\tilde{D}_t = k$, $k \in \{0,1,\ldots,S-1\}$, with probability $\tilde{p}_k = \sum_{i:k=d_i-\lfloor\frac{d_i}{S}\rfloor} p_i$.

The problem of deciding how to serve the remainders $\tilde{D}_t$ can be posed as the following dynamic program.

6.11 State variables

$x_t \in \{0,1,\ldots,S-1\}$ is the number of units available at stage t from an opened case pack of the packaging type under consideration

$\tilde{d}_t \in \{0,\ldots,S-1\}$ is the number of remainder units being ordered at stage t

$(x_t,\tilde{d}_t)$ is the state of our dynamic program. Note that there are S^2 possible states.

6.12 Control policies

$\mu_t \in \{W,O\}$ is the control at stage t. Where W denotes serving the remainder order observed at stage t, $\tilde{d}_t$, using a whole case pack of size S; and O denotes serving the remainder order observed at stage t, $\tilde{d}_t$, by picking individual units from an open case pack of size S (and opening a new case pack in the process, if necessary)

$\Pi = \{\mu_0, \mu_1, \ldots\}$ is a policy for the infinite horizon problem

6.13 Cost per stage

$g(x_t, \tilde{d}_t, \mu_t)$ is the cost incurred at stage t when applying control μ_t, and being in state $(x_t, \tilde{d}_t)$. Where $g(x_t, \tilde{d}_t, W) = P + C$, and $g(x_t, \tilde{d}_t, O) = V \cdot \tilde{d}_t + (P + K)\mathbb{1}_{\{\tilde{d}_t > x_t\}}$

6.14 State transitions

$(x_{t+1}, \tilde{d}_{t+1}) = (x_t, \tilde{D}_{t+1})$ if the control at stage t is $\mu_t = W$, and the uncertain remainder order at stage $(t+1)$ is $\tilde{D}_{t+1}$

$(x_{t+1}, \tilde{d}_{t+1}) = (x_t - \tilde{d}_t, \tilde{D}_{t+1})$ if the control at stage t is $\mu_t = O$, and $\tilde{d}_t \leq x_t$, and the uncertain remainder order at stage $(t+1)$ is $\tilde{D}_{t+1}$

$(x_{t+1}, \tilde{d}_{t+1}) = (x_t + S - \tilde{d}_t, \tilde{D}_{t+1})$ if the control at stage t is $\mu_t = O$, and $\tilde{d}_t > x_t$, and the uncertain remainder order at stage $(t+1)$ is $\tilde{D}_{t+1}$ (in this case it was necessary to open a new case pack of size S)

6.15 Long run average expected cost

$J_\Pi(x_0, \tilde{d}_0)$= Long run average expected cost induced by policy Π, starting from the initial state $(x_0, \tilde{d}_0)$. Note that $J_\Pi(x_0, \tilde{d}_0) = \limsup_{N\to\infty} \frac{1}{N}\mathbb{E}\left[\sum_{t=0}^{N-1} g(x_t, \tilde{d}_t, \mu_t)\right]$.

The problem that we are interested in solving is finding

$$J^*(x_0, \tilde{d}_0) = \min_{\Pi} J_\Pi(x_0, \tilde{d}_0),$$

for any initial state $(x_0, \tilde{d}_0)$.

6.16 Optimal solution

The following is the main result in this section.

Proposition 2 *For any given case pack size S and for any stage t there exists an optimal threshold policy to serve the remainder order $\tilde{d}_t$ at the distribution center.*

- *If the remainder order $\tilde{d}_t$ is larger than the threshold $\bar{d}$, then use a whole case pack.*
- *Otherwise pick the remainder order $\tilde{d}_t$ from an open case pack.*

Where the threshold $\bar{d}$ is such that

$$\frac{P+C}{\bar{d}} = V + \frac{P+K}{S} \tag{6.5}$$

Proof: From Proposition 4.2.1 in Bertsekas, Vol II [1] it follows that if there is a scalar λ, and a vector $\mathbf{h}$ that satisfy the Bellman equation

$$\lambda + h(x_t, \tilde{d}_t) = \min_{\mu_t \in \{O,W\}} \left[g(x_t, \tilde{d}_t, \mu_t) + \sum_{k=0}^{S-1} \tilde{p}_k h(x_{t+1}(x_t, \tilde{d}_t), k) \right], \tag{6.6}$$

for each state $(x_t, \tilde{d}_t)$, then $\lambda = J^*(x_0, \tilde{d}_0)$ is the optimal long run average expected cost starting from any state $(x_t, \tilde{d}_t)$. Furthermore, if there exists a control $\mu^*(x_t, \tilde{d}_t) \in \{O, W\}$, which attains the minimum in equation (6.6) for each state $(x_t, \tilde{d}_t)$, then the stationary policy $\Pi^* = \{\mu^*, \mu^*, \ldots\}$ is optimal, namely $J_{\Pi^*}(x_t, \tilde{d}_t) = \lambda$ for each state $(x_t, \tilde{d}_t)$.

Note that in our case the Bellman equation (6.6) simplifies to

$$\lambda + h(x,\tilde{d}) = \min\Big\{P + C + \textstyle\sum_{k=0}^{S-1} \tilde{p}_k h(x,k), \quad V \cdot \tilde{d} + \left(\displaystyle\sum_{k=0}^{S-1} \tilde{p}_k h(x-\tilde{d},k)\right) \mathbb{1}_{\{\tilde{d}\le x\}} + \left(P + K + \displaystyle\sum_{k=0}^{S-1} \tilde{p}_k h(x+S-\tilde{d},k)\right) \mathbb{1}_{\{\tilde{d}>x\}}\Big\} \quad (6.7)$$

We will guess the following functional form for the vector $\mathbf{h}$,

$$h(x,\tilde{d}) = h(0,\tilde{d}) - \alpha x. \quad (6.8)$$

Plugging in this functional form (6.8) into the Bellman equation (6.7), and simplifying, we get

$$\lambda + h(0,\tilde{d}) = \sum_{k=0}^{S-1} \tilde{p}_k h(0,k) + \min\left\{P + C, (V+\alpha)\cdot \tilde{d} + (P + K - \alpha S)\, \mathbb{1}_{\{\tilde{d}>x\}}\right\}. \quad (6.9)$$

Note that for equation (6.9) to hold for each state $(x,\tilde{d})$, it must be the case that

$$\alpha = \frac{P+K}{S}. \quad (6.10)$$

Then, equation (6.9) reduces to

$$\lambda + h(0,\tilde{d}) = \sum_{k=0}^{S-1} \tilde{p}_k h(0,k) + \min\left\{P + C, \left(V + \frac{P+K}{S}\right)\tilde{d}\right\}. \quad (6.11)$$

Taking the expectation over $\tilde{d}$ on both sides,and simplifying, we conclude

$$\lambda = (P+C)\mathbb{P}(\tilde{D} > \bar{d}) + \left(V + \frac{P+K}{S}\right)\mathbb{E}[\tilde{D}|\tilde{D} \le \bar{d}]\mathbb{P}(\tilde{D} \le \bar{d}), \quad (6.12)$$

where

$$\bar{d} = \frac{(P+C)S}{V \cdot S + P + K} \tag{6.13}$$

and $\tilde{D}$ is a random variable taking value $k \in \{0, \ldots, S-1\}$ with probability p_k. Note that Assumption 2 implies that $\bar{d} > 1$.

In order to pin down the vector $\mathbf{h}$, we will require that $h(S-1, 1) = 0$. Specifically, there are infinitely many vectors $\mathbf{h}$ that will satisfy equation (6.9) and we will pick one of them. More importantly, then the vector $\mathbf{h}$ has the interpretation of being the expected cost to reach state $(s-1, 1)$ from any other state for the first time. Plugging in the functional form (6.8), the definition of α in equation (6.10), and $\bar{d} > 1$, into equation (6.11), it follows that $h(S-1, 1) = 0$ is equivalent to

$$\sum_{k=0}^{S-1} \tilde{p}_k h(0, k) = \lambda + \left(\frac{P+K}{S}\right)(S-1) - \left(V + \frac{P+K}{S}\right) = \lambda + P + K - \left(V + 2\frac{P+K}{S}\right). \tag{6.14}$$

Finally, plugging in equation (6.14), the functional form (6.8), and the definition of α, in equation (6.10) in equation (6.11) we conclude

$$h(x, \tilde{d}) = -\left(V + \frac{P+K}{S}\right)x + P + K - \left(V + 2\frac{P+K}{S}\right) + \min\left\{P + C, \left(V + \frac{P+K}{S}\right)\tilde{d}\right\}. \tag{6.15}$$

In conclusion, by construction the scalar λ defined in equation (6.12), and the vector $\mathbf{h}$ defined in equation (6.15) satisfy the Bellman equation (6.7), therefore λ is the optimal long run average expected cost starting from any state $(x_t, \tilde{d}_t)$. Moreover, note that the control $\mu^*(x_t, \tilde{d}_t) \in \{O, W\}$, which attains the minimum in equation (6.6), for each state $(x_t, \tilde{d}_t)$, is a threshold policy which serves any remainder order $\tilde{d}_t > \bar{d}$ with a whole case pack, while any remainder order $\tilde{d}_t \leq \bar{d}$ is served from an opened case pack, where $\bar{d}$ is defined in equation (6.16), which is equivalent to equation (6.5) in the statement of the proposition. Therefore, this is a stationary optimal policy. ■

Note that the threshold $\bar{d}$ only depends on the cost parameters and on the case pack size S, and, surprisingly, it is independent of both the distribution of $\tilde{D}$, and the current number of items available from an opened case pack x. Moreover, the threshold has an intuitive closed form, which illustrates the interplay between the different cost parameters defined by the procurement department's case pack decision. Specifically, from equation (6.5) it follows that the threshold value $\bar{d}$ balances the per unit cost of using a whole case pack to serve a remainder order of size $\bar{d}$ on the left hand side, with the per unit cost of using an open case pack on the right hand side. In particular, on the left hand side of equation (6.5) we just divide the total cost of using a whole case pack by the number of units that we are satisfying $\bar{d}$, while on the right hand side we consider the cost of picking a single unit plus the total cost of using an open case pack, divided by the total number of units in the case pack S, because we know that we in the long run we will use all the units to satisfy some order.

This allows us to directly compute the supply chain costs induced by choosing any given case pack size, and then simply select the one with the smallest total cost as stated in the following corollary.

Corollary 1 *The total long run average expected cost induced by serving the orders using case packs of size S can be expressed as follows,*

$$\sum_{i=1}^{n}(P+C)p_i\left\lfloor\frac{d_i}{S}\right\rfloor+(P+C)\mathbb{P}(\tilde{D}>\bar{d})+\left(V+\frac{P+K}{S}\right)\mathbb{E}[\tilde{D}|\tilde{D}\leq\bar{d}]\mathbb{P}(\tilde{D}\leq\bar{d}),$$

where $\tilde{D}\equiv D-\lfloor\frac{D}{S}\rfloor$, and the optimal threshold policy to serve the remainders is defined by

$$\bar{d}=\frac{(P+C)S}{V\cdot S+P+K}.$$

Proof: The result follows directly by adding up equations (6.4) and (6.12). ■

Proposition 2 together with Corollary 1 provide a practical method to serve orders at the distribution center and select the best case pack size per SKU, respectively.

Square Washer Cost Comparison - Optimal Threshold vs. Exact Fulfillment			
Case Pack Quantity (# units)	50	50	250
Policy Type	Threshold	Exact Ful.	Exact Ful.\Threshold
Threshold (Units)	46	50	250
Total Cost ($)	64,367	64,375	67,903
Purchasing Cost($)	64,077	64,077	64,090
Purchasing % of Total	99.54%	99.53%	94.38%
Handling Cost ($)	290	298	3813
Handling % of Total	0.04516%	0.004632%	0.05615%
Extra Units Cost ($)	7,659	300	556

Table 6.1: Square Washer - Cost Comparison of Optimal Threshold Policy and Satisfying Orders Exactly

6.17 Application of Single Case Pack Optimization to the Square Washer

As an illustrative exercise, we will apply the deterministic demand single case pack optimization presented in this chapter to the square washer from TP&G. We will compare the success of the optimization to the policy of satisfying demand as ordered. It is important to note that while we are using the same demand data and set of potential sizes as in the simulation model, we will now not just look at handling costs, but also the purchasing costs (under no purchase price variance) comparisons between the results of the simulation model and this model should not be made. We have changed the cost structure slightly to remove some of the circumstances surrounding having open packs in the warehouse that are specific to TP&G. We assume in this model that the cost of breaking a pack is only attributable to the actual act of breaking the pack and the labor required, and not that plus the costs of missed cycle counts.

Table 6.1 shows the results of the optimization and compares the optimal policy with a policy of exact fulfillment. Table 6.1 also compares the results for a sub-optimal case pack quantity. In this case, we have chosen to evaluate a case pack of 250 washers, because this is the case pack quantity held in TP&G's inventory.

For the sub-optimal case pack, we calculated the optimal threshold policy and compared it to an exact fulfillment policy.

The optimal case pack quantity and policy combination is a case pack quantity of 50 with a threshold of 46. This threshold is high, thus, few orders are filled in excess of the ordered quantity.

If we look at a case where orders are fulfilled exactly as ordered (exact fulfillment), then the total cost increases slightly.

For the case pack of 250 washers, the optimal policy is a threshold policy of 250 units, which is equivalent to an exact fulfillment policy.

The results are actually intuitive in that, even for this relatively inexpensive item, the item is still cheap when compared to labor. In dollar terms, a square washer costs $0.26, which is equivalent to paying a material handler for 9 seconds of work at a wage of $20 per hour. Thus, if we are balancing laborers time versus unit cost, the decision will always be to have a worker pick individual units assuming that the cost of picking an individual unit does not exceed the unit price. Also, a higher breakpack penalty (such as in TP&G's case) would drive the threshold down from 46 units due to the increased cost of handling versus unit cost.

Comparing total cost directly yields results that might be seen as minimal or unimportant. After all, the total change in costs between the current practice (case pack of 250 with exact fulfillment) and the optimal practice (case pack of 50 washers with threshold policy of 46) is only $3,535 out of an original total of $67,090 (this is a reduction of 5.2%) which may seem small.

It is important to realize that this analysis applies only to one item which could be one of thousands of similar items. This is true for TP&G. Therefore, we can save 5% over the entire inventory. If we do a naive extrapolation and assume that there are 10,000 items in TP&G's inventory and that they are all identical to our washer, the resulting savings are approximately \$35.5 MM. That is not insignificant for any company. Of course, the actual savings are actually likely different, but over the supply chain of any company 5% savings year over year quickly add up to significant results.

Another key aspect of this analysis to note is the source of the difference in total cost. The difference in total coast is almost entirely contributable to a reduction in handling costs (of the \$3,535 difference, \$3,522 is from reduction in handling costs).

This answers a main question that motivated the research behind this thesis about whether or not case pack quantities (and procurement decsions about them) have any effect on costs in the rest of the supply chain. We can now say they do.

The marginal cost between the optimal case pack quantity and policy and the case pack quantity currently held in inventory is equivalent to 176 man hours of work at a wage of \$20 per hour. That is an additional 4.4 weeks of time in a year that material handlers must spend handling just washers.

Our analysis presents a framework for analyzing the impact of case packs. This framework does not take into account the effects (costs) of other adjacent problems that could be associated. For example, if material handlers are overcapacity, lead times are likely excessively high as a result, and much overtime is being paid to accomplish the work needed. If given the chance, any rational manager would increase his yearly capacity by 176 man hours if given the opportunity.

Again, this analysis applies to one item. Applying this analysis across a company's inventory could result in a significant reduction of completely superfluous handling time and a significant increase in material handling capacity.

6.18 Conclusions of Optimization

The conclusions of the models and proofs presented in both Section 6.7 (deterministic demand) and Section 6.8 (stochastic demand) are powerful for procurement personnel and warehouse managers.

For warehouse managers, the results are perhaps more powerful, particularly in the stochastic demand case. Even without a change in case pack quantities, the optimal picking policy is a stationary threshold policy, for which the threshold can be computed using Equation 6.16. A warehouse manager only needs to know the costs associated with picking to set an optimal policy for any given item.

The threshold is merely a ratio balancing the costs of picking from whole boxes and the costs of picking individual units from open packs. All the costs can be calculated using the task wage framework presented in Section 3.4.

Optimization Conclusions for Warehouse Managers

Whether or not the optimal case pack quantity is held in inventory, the optimal picking (in a stochastic demand case) is a stationary threshold policy. The threshold is calculated using Equation 6.16:

$$\bar{d} = \frac{(P+C)S}{V \cdot S + P + K} \tag{6.16}$$

If, after first filling an ordered quantity with whole case packs of a material, there is a remainder to be filled, if that remainder is above the threshold policy, the remainder should be filled with a whole case pack, even if that means sending more units than ordered. If the remainder is below the threshold, the material handler should pick individual units from an open box and exactly satisfy the ordered quantity.

Figure 6-1: Conclusions of Optimization for Warehouse Managers

Optimization Conclusions for Procurement

We have presented a quantitative method by which procurement personnel can select case pack quantities for which total costs are minimized (purchasing + handling costs), assuming the warehouse follows the optimal picking policy, which is a threshold policy as described in Figure 6-1

Figure 6-2: Conclusions of Optimization for Procurement Personnel

Simply stated, procurement personnel should conclude that cost optimal case pack quantities can be efficiently computed given a demand set.

Chapter 7

Conclusions

7.1 Model Conclusions and Recommendations

7.1.1 Optimal Policy Conclusions

The most powerful result of the optimization is that we have proven that the optimal picking/fulfillment policy is a stationary threshold policy indicating when to serve demand from individual units or with whole boxes and that policy is related to the handling cost components. This type of analysis can be applied to even sub-optimal case pack quantities and achieve great results.

7.1.2 Optimal Case Pack Quantity Conclusions

Though not as powerful as the policy result, We have also demonstrated that organizations (TP&G, in particular) can achieve significant by analyzing demand and choosing to hold in inventory a case pack quantity which is a factor of the modes of demand. For example, if customers tend to order an item in multiples of 50, then the cost minimizing case pack quantity is likely to be 50 units.

In our analysis we assumed that there would be no purchase price variance for ordering any case pack quantity of a given item. We had to make this assumption due to a lack of realistic data or estimates. If this data is found in the future, our model becomes more useful in decision making because there is now a tradeoff in purchasing costs to analyze against handling and misallocated unit costs.

A general result that any procurement professional can carry forward without applying the model is that matching ordered case pack quantities to how customers order (and therefore use) a given material can result in significant cost savings for any organization that deals with handling materials to fulfill orders.

7.2 Recommendations for TP&G Procurement

7.2.1 Implementation of the Model

TP&G has over 10,000 unique items in their inventory, all of which will be included in a sourcing event in one to three years. We highly encourage TP&G procurement personnel to use our model as a decision assistance tool in upcoming sourcing events.

Currently case pack quantities are chosen in sourcing events through a mix of old wisdom and unsystematically gained new wisdom. The model created here can provide another dimension to the procurement decisions cycle that could provide a great deal of savings to TP&G.

7.2.2 Engaging Suppliers

We highly recommend that TP&G procurement personnel across all material groups and categories engage a subset of suppliers in negotiations regarding case pack sizes to build on our work here and understand more fully the possibilities and implications of ordering or changing case pack quantities from historical quantities.

7.3 Recommendations for TP&G Warehouse Management

7.3.1 Remove Rule of Thumb

In light of our results, we recommend the immediate adoption of policies in which demand is always fulfilled. In the best case, this is a prescriptive rule of thumb as demonstrated in our optimization results. Even adopting a breakpack policy would be highly beneficial to all parties in TP&G (under strict process control).

The adoption of a policy in which all orders are fulfilled as ordered will, in the long run eliminate "fire drills" stemming from not fulfilling orders and should result in more predictable and stable work.

7.3.2 Investigation and Development of Handling Procedures for Spooled Items

We highly recommend that TP&G investigate ways in which to handle spooled items more effectively. Most managers we talked to across the supply chain have a nagging feeling that the way in which spooled items (particularly cable) is handled is less than optimal. Our simulation model has quantified this result and we hope it gives TP&G warehouse management personnel support in claiming resources to develop a system to better handle spooled items.

7.3.3 Investment in More Capacity

In our experience, the warehouse workers of TP&G are, across the board, working at full capacity. Therefore, all efforts were and are directed towards execution. Almost no resources are devoted to process improvement/development or experimentation within the warehouses.

We highly recommend that TP&G invest in hiring more workers who can absorb excess demand in peak times and allow for experimentation and development/improvement of processes in "slack" times. Many of the workers in the warehouses are brilliant, know the problems in their processes, yet repeat the same costly errors over and over again because there is no time to fully develop or scale solutions. We believe that TP&G could save much more than the cost of hiring a few additional employees through experimentation and process improvement.

7.4 Recommendations for TP&G Executives

Through our research, we wanted to pursue a project that had potential to provide a "good news story" about how siloed organizations can work together to achieve better results for TP&G, when compared to acting strictly on local incentives. This was in accordance with the desire of TP&G executives to have such a good news story.

We are pleased that our research resulted in what can be construed as a good news story of how different functional organizations within TP&G can potentially work together to achieve great results.

We recommend that TP&G executives not only continue to develop research based on the foundation we have put forth in this thesis, but also continue to promote research oriented towards aligning organizations to TP&G outcomes. Investment in research and a research oriented culture will pay dividends for TP&G in the future (literally).

7.5 Conclusion

Significant cost reductions can be achieved through the optimization of case pack quantities by applying the framework and models built in this thesis.

The results presented were found in the environment of TP&G, yet the framework developed and methods applied here are generalizable and applicable to any organization which performs procurement and fulfillment functions.

At the time of writing, not much published research exists around case pack quantity optimization. We have shown that case pack optimization shows great potential to save organizations a great deal of money and have pointed out where our research ends and could potentially be extended (e.g. cost of unfulfilled orders, purchase price variance with case pack quantities). We hope the presented thesis will provide a firm foundation for future researchers in this area and will spur interest in the academic community around this potentially lucrative yet, thus far, overlooked corner of operations management and research.

THIS PAGE INTENTIONALLY LEFT BLANK

Bibliography

[1] Dimitri P. Bertsekas. *Dynamic programming and optimal control / Dimitri P. Bertsekas.* Belmont, Mass. : Athena Scientific, c1995., 1995.

[2] C. Bongers. *Standardization : mathematical methods in assortment determination / C. Bongers.* Boston : M. Nijhoff Pub., c1980., 1980.

[3] Gerard P. Cachon and Marshall Fisher. Supply chain inventory management and the value of shared information. *Management Science*, 46(8):1032, August 2000.

[4] Ren de Koster, Tho Le-Duc, and Kees Jan Roodbergen. Design and control of warehouse order picking: A literature review. *European Journal of Operational Research*, 182(2):481–501, October 2007.

[5] Jinxiang Gu, Marc Goetschalckx, and Leon F. McGinnis. Research on warehouse operation: A comprehensive review. *European Journal of Operational Research*, 177(1):1–21, February 2007.

[6] David W. Pentico. The assortment problem: A survey. *European Journal of Operational Research*, 190(2):295–309, October 2008.

[7] James A. Tompkins. *Facilities planning / James A. Tompkins ... [et al.].* Hoboken, NJ : J. Wiley, c2003., 2003.

[8] Karel H. van Donselaar, Vishal Gaur, Tom van Woensel, Rob A. C. M. Broekmeulen, and Jan C. Fransoo. Ordering behavior in retail stores and implications for automated replenishment. *Management Science*, 56(5):766–784, May 2010.

[9] Gerhard Wscher, Heike Hauner, and Holger Schumann. An improved typology of cutting and packing problems. *European Journal of Operational Research*, 183(3):1109–1130, December 2007.

[10] Paul Herbert Zipkin. *Foundations of inventory management / Paul H. Zipkin.* Irwin/McGraw-Hill series. Operations and decision sciences. Boston : McGraw-Hill, 2000., 2000.