ABSTRACT

Title of Document:	OPTIMIZING LIFETIME BUY QUANTITIES TO MINIMIZE LIFECYCLE COST
	Dan Feng, Master of Science in Mechanical Engineering, 2007
Directed By:	Associate Professor, Peter Sandborn, Mechanical Engineering

Mismatches between electronic part procurement lifecycles and the lifecycles of the products they are used in causes products with long manufacturing and/or support lives to suffer from significant obsolescence management costs. Lifetime buy is a prevalent mitigation approach employed for electronic part obsolescence management. Making lifetime purchases of parts upon obsolescence involves managing interacting influences and concurrent buys for multiple parts in a sequential manner. This thesis is focused on optimizing lifetime buy quantities by minimizing lifecycle cost.

The Life of Type Evaluation (LOTE) tool was created to optimize lifetime buy quantities. LOTE requires component and system data and expected demand information. With the given data, LOTE uses stochastic analysis to determine the lifetime buy quantity per part that minimizes the lifecycle cost for the system.

Results from a LOTE analysis of a Motorola communication system indicate that organizations may be systematically overbuying at lifetime buys giving inventory shortage penalties a greater emphasis than other hidden costs.

OPTIMIZING LIFETIME BUY QUANTITIES TO MINIMIZE LIFECYCLE COST

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2007

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Acknowledgements

I would like to thank my advisor Professor Peter Sandborn. He had provided valuable guidance and advice for areas related to my research and beyond. He has been incredibly patient and understanding, and has dedicated a great deal of time to help me with my research.

Additionally, I would like to thank my friends Jessica Myers and Rifat Jafreen who share an office with me. They have put up with me when I was frustrated, confused, and stressed out and have still remained great friends.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Overview of Electronic Part Obsolescence

Electronics has become an indispensable part of the consumer market. The electronic industry has been growing and continues to do so at a fast pace. From the early 1990's to 2000, the electronic industry has grown three times faster than the overall economy [5]. Intel's market capitalization was larger than the three largest US automakers combined [20]. The growth of the electronic part industry has influenced the rate at which electronic parts change. Changes in electronic parts include increased component operating speed, reduced feature size, reduced supply voltage, interconnection changes, and higher density packing technologies. These changes occur almost monthly. In 1965, Intel's founder, Gordon Moore predicted that processing power of transistors (now microprocessors) would double every 18 months. This prediction is known as Moore's law, Figure 1 [23].

$$\frac{dN}{dt} = rN$$
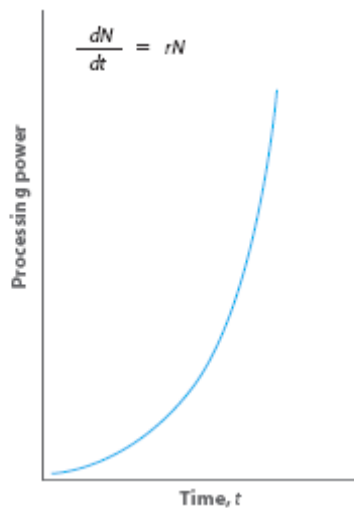
Figure 1. Moore's law of processing power versus time (N = number of transistors per square inch on an integrated circuit, r = rate of increase) [16].

With changes and improvements in electronic parts occurring so rapidly, product procurement life decreases because the consumer market place demands cutting edge technology. Part suppliers are pressured to keep up with technology advancements and make more profitable products with improved features. Small products (e.g., cell phones, iPods) have a disposability factor, i.e., they are created to be used and disposed of within 1 to 2 years, rather than maintained over 10 to 20 years [16]. However, decreases in procurement life of parts become injurious to products that have lifecycles that are significantly longer than the parts they are made of [3, 20].

The aircraft industry is an excellent example of a mismatch in part lifecycle and system lifecycle. Thousands of electronic or computerized parts make up an aircraft and each aircraft is expected to last 20 to 30 years. This system life is approximately 10 times longer than the procurement life of many of the electronic parts [16]. Over 20 to 30 years, thousands of parts for a single aircraft alone face obsolescence every 1 to 2 years. This is a serious problem faced not only with aircraft but other military equipment, factory equipment, and ships.

A similar dilemma is faced in the consumer industry. Electronic products can be categorized into two types, cutting edge and workhorse [20]. For cutting edge products, the application drives the market and part procurement life. Workhorse products, however, are expected to maintain for a long period. The difference between cutting edge and workhorse products might be analogous to the difference between the HD television for a home entertainment center and a CRT television for security monitoring. Consumers expect the HD television to be the latest technology and to obsolete itself every few months (larger, thinner, cheaper, etc.), while the

security monitor is expected to have high quality and long life. While the HD television will be phased out by the next latest and greatest model within a short life time, the security screen components must be available for a much longer time.

When the demand for a part drops so low that the manufacturer can make more profitable use of the resources elsewhere, or when the materials and/or technology to produce the parts is no longer available, then the manufacturer stops making the part [23]. The part is considered obsolete when it is no longer available from the original manufacturer. For those that depend on the part to maintain their product, this is a significant problem.

The military, the largest holder of long-term assets, faces the part obsolescence issue continuously [23]. In fact, they have named this issue the Diminishing Manufacturing Sources and Materials Shortage (DMSMS) problem [28].

1.2 Obsolescence Management Methods

To deal with part obsolescence, a variety of strategies have been developed: redesign/refresh,[1] life of type buy, reclamation, substitute or alternate part, emulation, aftermarket source, and uprating [29]. These all have their benefits and drawbacks that will be discussed.

Redesign is considered one of the most expensive solutions. The US Deputy Undersecretary of Defense for Logistics (DUSD(L)) estimated on average the cost to redesign a circuit card to eliminate an obsolete part is USD$250,000 [16]. That

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[1] Design refresh refers to designing out obsolete parts while leaving the functionality and performance of the system approximately unchanged. Redesign refers to designing out the obsolete parts while at the same time upgrading the functionality or performance of the system.

includes the cost to reverse engineer a design and certify all new parts. Usually this approach is used as a last resort and is considered reactive rather than proactive. The downside to this method is that it may delay critical deadlines, extend production periods, suspend production lines, and incur expensive non-recurring (NRE) or one time costs [16, 19].

Life of type (LOT) or lifetime buy (LTB) (also called final order purchases) refers to making enough purchases of the original part for the forecasted lifetime demand or until a redesign (bridge buys). It is a combination of forecasting, prevention, and strategic management. One downside of lifetime buys is that a large expenditure is required initially and supply for the entire lifetime is not guaranteed. Parts may become unusable over time due to oxidation, dust, dried parts, discoloration, or more [16, 23].

Reclamation refers to salvaging the same parts from an existing product. This method requires the right conditions. There must be enough parts to meet the quantity requirements, the quality can be verified, and the existing product from which the part will be salvaged must be unused and will not need the part in the future. The largest downside to this approach is that one does not generally know what portion of the salvaged part's reliability life remains. This approach also generally requires extra labor to extract the part from the existing product [16, 23].

Substitution, alternate parts, emulated parts, and aftermarket sources are all similar approaches to obtain obsolete parts. Emulated parts have the same form, fit and function, while substitution refers to using a part with the same form and greater than or equal function and performance. Alternate parts have similar form and lesser

function and performance. Although substitute and alternate parts may be the least expensive of all the options, these methods may require obsolescence planning during the initial design phase and an up-to-date analysis of the market at the time, which may not be available [16, 23].

Lastly, uprating refers to using parts outside of the manufacturer specifications. Usually parts are used outside of their recommended temperature rating. This is a common method for using commercial off-the-shelf (COTS) parts in military applications. MIL-SPEC parts are parts specifically rated for military applications. When MIL-SPEC parts become obsolete, the same part may still be available in the commercial marketplace, but may be rated to a lower temperature [20, 29].

All of these approaches are viable management solutions to the DMSMS problem. Either a single approach or a combination of these solutions is used to manage part obsolescence and sustain a product for its lifecycle. Some of these solutions require careful planning starting at the design phase to take into account component obsolescence, while others are more reactive to obsolescence as it occurs.

1.3 Lifetime Buy[2]

Lifetime and bridge buys are the most frequently used mitigation methods in military and commercial industries. Lifetime buys and bridge buys can be applied to products still in the design phase, in production, or during product sustainment.

Lifetime buy purchases involve generating demand forecasts and using those forecasts to decide lifetime buy quantities. Demand forecasting is an area of study on

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[2] Lifetime buys have also been referred to as Life Of Type (LOT) buys, last time buys, and final order purchases.

its own, not discussed in this thesis. The focus of this research is to optimize the lifetime and bridge buy quantities to minimize lifecycle cost based on uncertain demand forecasts.

From the product manufacturer view point, bridge buys and lifetime buys for single components of a large multi-component product affect that product's sustainment cost[3] (lifecycle cost) and overall revenue generation. The cost associated with lifetime buy is affected by a variety of factors contributing to the complexity of its analysis. Figure 2 shows the factors affecting the lifetime buy cost: procurement cost inventory cost, disposition cost, and penalty cost. Each of these costs has its own contributing elements. For example, penalty cost is a summation of the alternative sources availability cost, system unavailability cost, inventory shortage cost, equal run-out cost, and more.

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[3] Costs related to keeping an existing system operational (able to successfully complete its intended purpose), continuing to manufacture and field versions of the system that satisfy the original requirement, and manufacturing and fielding revised versions of the system that satisfy evolving requirements[17].
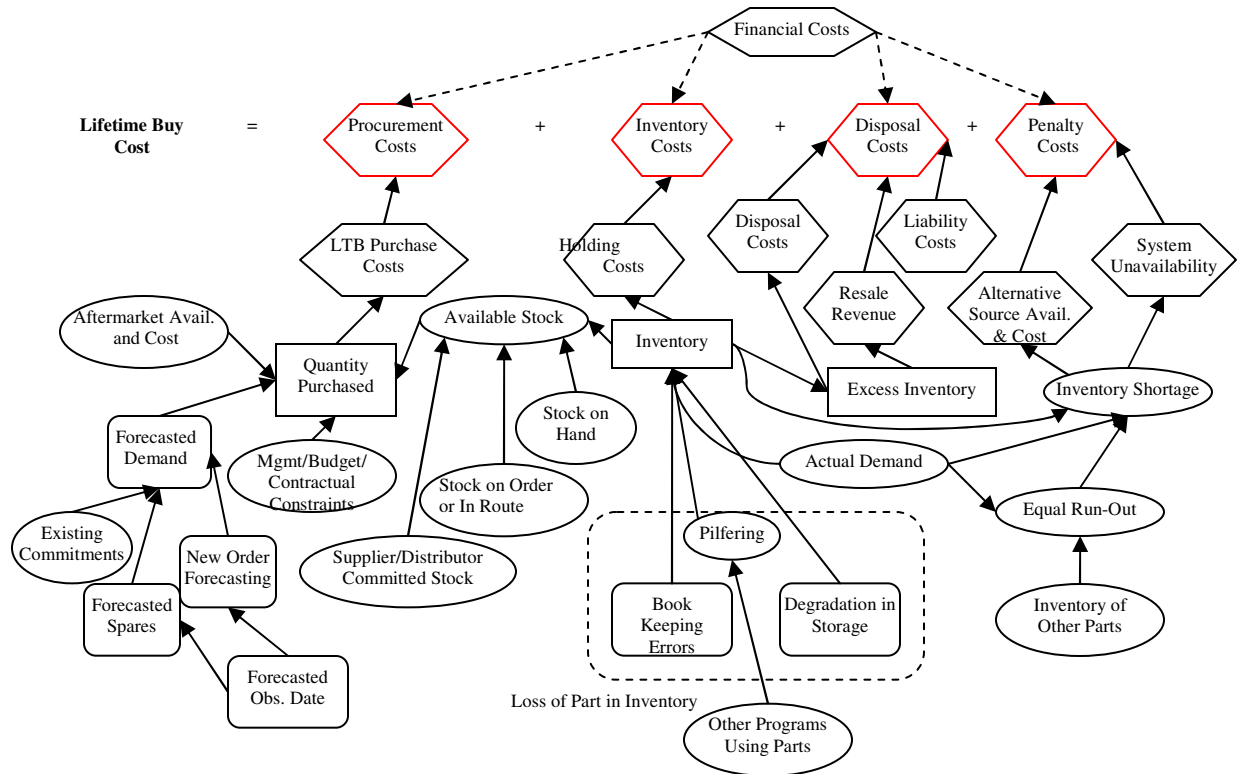
Figure 2. Factors contributing to lifetime buy cost.

Lifetime buy cost consists of four major components; procurement cost, inventory cost, disposition cost, and penalty cost. As seen in Figure 2, each of these costs is composed of a set of interacting factors. Procurement costs refer to the finances needed to purchase the required number of parts at the lifetime buy. Determining the procurement quantity requires consideration of the available stock, the available budget to make purchases, costs to procure parts from the original supplier or a third party (aftermarket) source, and the forecasted demand.

Once acquired, parts must be managed in inventory for long periods of time (some lifetime buys include parts held in inventory for 20 years or more). Factors that affect inventory cost include accounting costs, storage costs, maintenance costs while in storage, loss of parts to other programs ("pilfering"), and loss of parts

through degradation (e.g., oxidation, discoloration, rust, etc.). Toward the end of the product lifetime, there are also costs to dispose of unused parts. Depending on the part, special measures may be required for disposition to protect the environment. Or, excess parts may be resold to a broker or recycled in other programs and incur a negative disposal cost that add to the value of the existing program.

Penalties are involved at all stages of a lifetime buy. At acquisition, if parts are unavailable through the original supplier, third party sources may charge prices that are multiple times the original price. During the inventory stage, penalties can be incurred if there is a shortage of even one part. When there is a shortage, if the part is available through aftermarket sources, there may be an availability penalty associated with higher-priced parts. If the part is unavailable through any source, the penalties can be even greater. In this case the penalty may be from loss of the ability to support a fielded system, loss of a customer, or loss of profit associated with not being able to sell a product.

In situations when a part becomes obsolete and is unavailable, the effect of that part's run-out on all other parts in the system is known as "equal run-out" or "matched set." All parts in a system are assumed to be critical to product. When one part's stock is completely drawn and it cannot be obtained through any other source, all other parts still remaining in stock cannot be used. The product becomes unavailable and all remainder parts in stock must be disposed and may incur disposal fees depending on the disposition method used.

In making lifetime and bridge buys, customers must balance all the contributing factors discussed above and monitor their affects on the overall sustainment cost of a

product. The objective is to minimize sustainment cost. To do so, the customer must balance between the procurement and inventory costs with the cost of any penalties from available third party sources or unavailability penalty. Since demand is an uncertain target, purchasing greater than a predicted demand may increase sustainment costs due to procurement and holding costs. However, purchasing less than actually required may incur other penalties. To minimize sustainment cost, the customer must choose an optimum lifetime buy quantity that accounts for all the influencing factors and their uncertainties.

This research problem is similar to the classic newsvendor optimization problem [11]. In the early part of the century, newspapers were predominately distributed by publishers and sold through newsvendors and newsboys. At the start of each day, the newsvendor had to predict based on various factors (e.g., headlines in the paper, weather conditions, day of the week) the number of papers they could sell that day. The dilemma was in making the prediction. If the newsvendor purchased more papers than he sold that day, there was an overstock penalty. However, if the newsvendor purchased fewer papers than were in demand for the day, he lost profit. It is an optimization problem that has evolved with time. Currently, manufacturers and product-based companies face the same problem. However, it has morphed into a more complex problem involving multiple interrelated parts with varying demands and manufacturing situations that support more than one system.

1.4 Inventory Obsolescence Modeling and the Final Order Problem

In obsolescence management, there are two different perspectives to the obsolescence problem. Obsolescence as it is being used in this thesis refers to the end of procurement date for a specific part. Product manufacturers with products that depend on those parts must learn to deal with part obsolescence. This is known as the final order problem or lifetime buy problem discussed above. The type of obsolescence that this thesis is treating is referred to as DMSMS (Diminishing Manufacturing Sources and Material Shortages) or involuntary obsolescence, because it is forced upon product manufacturers.

However, obsolescence has also been defined as an inventory issue. Inventory or sudden obsolescence refers to an inventory of parts that is suddenly no longer in demand - e.g., product upgraded, product line termination, etc., have reduced the demand for an existing inventory of supporting parts to zero. Inventory or sudden obsolescence is defined as a "high likelihood that demand will drop substantially from its current level" [2]. In this case, the part supplier must deal with the low part demand and excess parts in inventory.

In the inventory obsolescence scenario, some components may inherit their inventory needs from the products they supply. This is especially the case if the part supplier's customers are concentrated and well-defined. If the part supplier realizes that demand from its customers is decreasing, it may require a final buy from product manufacturers. Obsolescence is driven by the products they support. In this situation, there is a balance to maintain between costs to product manufacturer for inventorying parts versus costs to part suppliers for producing parts with diminishing demands.

The part supplier does not want to support a part if it is not profitable. Likewise, product manufacturer does not want to keep parts in inventory [12].

Currently there are a range of theoretical solutions from simple to complex for the inventory obsolescence problem. These solutions generate various types of demand distributions to determine the optimum stocking level for the part supplier to minimize cost. Though these solutions are not directed at the final order problem (the DMSMS or involuntary obsolescence problem), they do represent early research that potentially contributes to the final order solution model.

A simple inventory obsolescence model assumes a constant demand rate, where a random outside event causes obsolescence or decrease in product demand. This same demand assumption can be used for the final order problem. The lifetime is assumed to be a random variable modeled by a known distribution. Using these assumptions, the simple model finds the optimal stocking level to minimize costs. The Brown (1971) [1], Masters (1991) [10], Joglekar and Lee (1993) [7] models assume an exponential distribution for product lifetime along with the constant demand [1, 2, 7, 10]. The David et al. model assume other lifetime distribution [2, 4].

More complex models assume each period's demand is randomly distributed (stochastic). These discrete-time dynamic problems are solved numerically. Pieskalla (1969) models the lifecycle problem as a finite-horizon inventory problem [2, 15], where there is a definite period the problem is considered within. The demand is distributed independently, but identically at each discrete-time period. It uses prior probability to predict product obsolescence in a future period. The Pieskalla model demonstrated regardless of the probability distribution used the

11

difference in the optimal solutions between models with and without consideration of inventory obsolescence decreases with increase in the number of periods [2, 15].

Another approach to this same inventory issue is using Markov Chains. Brown et al. and Song and Zipkin both proposed models analyzed using Markov Chains [2, 7, 15, 21]. The Brown et al. research models demand distribution as a function of demand-generating states that form a discrete-time Markov Chain. This model minimizes the total discounted cost over an infinite horizon [2, 7]. The Song and Zipkin model considers the demand has a Poisson distribution. Parameters that generate the demand depend on states of the world [2, 21], where the world acts as a continuous-time Markov-Chain [2, 21]. In addition, this model assumes the ordering costs are fixed, and the lead times are stochastic. The intention is the same as the Brown et al. model, to minimize total discounted cost [2, 7, 15, 21].

These models offered research and solutions to the inventory obsolescence problem. They offer insight into modeling uncertain demands, and offer solutions that minimize cost to inventory parts given uncertain lifecycles. The models mentioned above do not directly deal with the lifetime buy problem. The lifetime buy problem also seeks a minimized cost solution. Without a well-defined product driven demand, part manufacturers usually offer lifetime buys opportunities to their customers when they (the part manufacturer) can do something more profitable with the resources they are using to manufacture the part. Product manufacturers are forced to decide whether they want to make a last time or lifetime buy purchase and if so, the quantity. Product manufacturers start with a demand forecast provided by an outside source (e.g., a marketing or sales organization). With the demand input, information on the bill of

materials, details about the part's obsolescence and production information, final order models transform the data into usable information about lifetime buy purchasing quantities and lifecycle costs.

Research conducted by Teunter and Fortuin (1998) and Fortuin (1980) focused directly on final order purchases. From the inventory obsolescence models, the final order models evolved to consider the level of service (e.g., lifetime buy, bridge buy) in calculating the number of parts to purchase for a finite period after obsolescence. Both Teunter and Fortuin assume that a company must stock parts for a certain period after the end of production. Fortuin's model assumed independent demand distributed normally [6]. The distribution mean exponentially decreased with time to mimic decreasing demand in practical applications. Teunter and Fortuin introduced the concept of holding costs, penalty costs, and disposal costs [2, 26]. The Teunter and Fortuin model assumes demand is a Poisson distributed process with period dependent rates. It is a multi-period inventory problem. Inventory costs are allocated starting at obsolescence and end when the lifecycle concludes. The final order or purchase is made in the first time period only for each part. The Teunter model has shown to be a good approximation for high penalty cost problems [27].

1.5 Summary of Research

The work done in this thesis focuses on DMSMS obsolescence and the lifetime buy problem for electronic parts. The goal is to create a practical model that includes the factors affecting DMSMS obsolescence and lifecycle cost, and use this model to

minimize lifecycle cost through lifetime buy quantity optimization. The work in this thesis is organized into three parts:

1) Model Extension - The work of Teunter and Fortuin on the final order problem is relevant to the lifetime buy of electronic parts, but was developed for application to a different class of problems, e.g., to purchasing and storing spare parts for manufacturing equipment [25]. As such, the final order problem treatment must be extended and generalized to include multi-part analysis (Teunter and Fortuin solve the problem for one part at a time), refreshes or redesigns, varying demand profiles with a number of stochastic distribution options, and a practical search algorithm for efficient solution generation.

2) Evaluation and Validation of the Model – A controlled set of simple example problems were formulated to test the model formulation.

3) Application of the Model to a Real Problem – The model is used to evaluate the Infrastracture Base Station from Motorola. The Base Station has to be supported for 16 years and will have 277 lifetime buys and bridge buys of parts during its support life.

The model developed in this thesis is the first known attempt to extend and apply final order modeling to optimizing lifetime buy quantities to electronic part obsolescence management.

Chapter 2: Lifetime Buy (Final Order) Modeling

Teunter and Fortuin [25] created a final order model that solves for the optimum lifetime buy quantity of parts to purchase at part obsolescence and used it on a Philips case study [26].

This thesis builds on Teunter and Fortuin's model and converts the model into a practical methodology that can be utilized for the electronic part lifetime buy problem. The methodology also adds, to the Teunter Fortuin model, the ability to solve for problems with refresh dates, look-ahead times, and demand variations. The methodology also solves for a lifecycle cost of an entire system of obsolete parts rather than one part at a time. The uncertainties relating to demand and penalties are modeled through stochastic distributions in the methodology. And, to reduce analysis time, a gradient search algorithm is utilized. This chapter describes the Teunter and Fortuin model, the extensions that have been made to it, and discusses the implementation of the model into the LOTE tool.

2.1 Teunter and Fortuin Model

The basic model used for this body of research extends the work of Teunter and Fortuin [25]. Their research models the lifetime buy (also known as final order or life of type) purchase problem faced in industry. As described in Chapter 1, lifetime buy purchasing is a popular solution for dealing with part obsolescence. Lifetime buy purchases are made at a the risk of purchasing either more or less than demand. In either situation, there are unwanted costs that drive up lifecycle cost. Teunter and Fortuin models this problem using various cost factors (procurement, inventory,

disposal, and penalty) and analyzes the problem to minimize lifecycle cost by balancing all cost factors through optimizing the lifetime buy quantity of parts upon obsolescence. The model iterates through the product lifecycle by user specified time periods and accumulates costs that contribute to sustainment at each time step.

The Teunter model (also the Teunter and Fortuin model) is the foundation used in this research. It assumes a finite time span that starts at $t = 0$ (D_0) and ends at $t = L$ (D_e). The planning horizon or product lifecycle is L, in years. The start date denotes the beginning of the analysis and the end date represents the end of system support for lifetime buys or planned design refreshes for bridge buys. The analysis is divided into user defined time step lengths T. For each part in the system, at each time step, the model records the part inventory level, procurement cost, holding (inventory) cost, and accumulated penalty cost. When a part goes obsolete and a lifetime buy needs to be made, at the first time step for each part, procurement costs are incurred along with holding cost for storage of all procured parts. At each subsequent time step, the holding cost decreases as the quantity decreases with part usage. If the inventory of lifetime buy parts runs out, penalties are incurred. These costs are summed together for all time steps in order to obtain a single lifecycle cost for the entire system. Any remaining parts in stock at the end of the system life that are not required to meet demands are disposed of. They may be salvaged, resold, or removed at a fee that is also summed into the lifecycle cost at the final time step.

This model operates under a set of assumptions. The planning horizon is divided into T intervals of length L/m where m is a user specified length (e.g., years, months, weeks, quarters, etc.). The analysis time intervals are represented by j and span $[j - 1,$

j), *j* = 1, 2,…, *T*. The demand and supply are allotted at the end of the interval, and the supply can fill the demand in the same interval. Penalty costs are allocated at the end of the interval, and holding costs are allocated at the beginning of the interval. For all intervals, the demand and supply distributions are known and are assumed to be independent.

The mathematical cost model for a single part (*i*) is represented in (1). The objective is to minimize the value of the following expression over all $n_i \geq 0$, [25]

$$a^{j_i-1}c_i n_i + \underset{s_j,D_j}{E}\left[\left(\sum_{j=j_i}^{T}a^{j-1}\left(\frac{h_i}{12}S_{j(i)}+ap_i\left(S_{j(i)}+\left(s_j-d_j\right)q_i\right)^{-}\right)\right)+a^T r_i\left(S_{T(i)}+\left(s_T-d_T\right)q_i\right)^{+}\right]$$

(1)

where,

a	Function of the discount factor ($e^{-R/12}$), *R = time in years from start date*
c_i	Initial purchase cost of the part *i* (present when $t = t_i$)
n_i	Final order purchase quantity for part *i* at the beginning of time step 1
s_j	Supply of system parts (quantity distribution), in j^{th} time step (i.e., substitution, emulation, alternate part from retired/alternate source)
E[]	Expected value
d_j	Demand of system parts (quantity distribution), in j^{th} time step
D_j	Date corresponding to the current time step *j*
h_i	Holding cost for part *i* (present when $t > t_i$)
$S_{j(i)}$	Stock at the beginning of interval *j* for part *i*; $S_1 = n_i$
p_i	Penalty cost of part *i* if it is obsolete but available from alternative sources
p_{su}	Penalty cost of system if any of its parts is unavailable from all possible sources
r_i	Remove/residual cost of part *i* (parts removed at the end of life)
J	Index of the current time step
T	Time
t_s	Time step (in years)
O_i	Date of obsolescence for part *i*
G	Total expected discounted cost for a given stock quantity (n_i)
q_i	Instance of part *i* in a system

2.2 Modified Teunter and Fortuin Model[4]

The Teunter and Fortuin [25] model was extended for use in this research. The extended Teunter and Fortuin model adds system unavailability penalty (loss of profit) to the Teunter and Fortuin model. Teunter and Fortuin's model was a part-specific model, for this research, the model was extended to determine part-specific optimum buy sizes based on minimization of lifecycle costs for an entire system of parts. This extension was inspired by the highly coupled nature of electronic component lifetime buy problems. The model is also implemented in a stochastically general way allowing all variables to be described by unique probability distributions – Teunter and Fortuin's original model only supported a Poisson distribution on demand.

Rather than representing the model as a single formula as with the original Teunter and Fortuin model, the modified expression is divided into a series of sub-expressions. The constituent electronic parts are indexed by i. The net present value of all sub-expressions is calculated at D_0 assuming a discount rate of R. The first contributing cost is the initial purchase cost (procurement cost) at the required quantity (N) after the part becomes obsolete for a pre-determined period, C_p. C_p is given in (2), and is implemented at $t = 0$.

$$C_p = \sum_{i=1}^{N} \frac{c_i n_i}{\left(1 + R/100\right)^{(O_i - D_0)}} \tag{2}$$

The modified expressions give the cost of obsolescence mitigation throughout the part's lifecycle, but do not account for costs before or after the lifecycle. The

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[4] A portion of the modifications to the formulation of the Teunter and Fortuin's model were made by P. Singh at the University of Maryland. These modifications have not, however, been published to date.

procurement cost is equal to the net present value of all procurement costs for all parts that become obsolete and have to be lifetime bought. The procurement cost for a single obsolete part in the system is the product of the part cost per unit and the quantity of parts required.

If a part's purchased quantity (lifetime buy) runs short a penalty cost p will be incurred if the part is still available. Penalties may be a result of using a third party source or a resurrection[5] from the original source. Penalty cost (C_{pc}) in given in (3).

$$C_{pc} = \sum_{j=1}^{T} \sum_{i=1}^{N} \frac{p_i \left(S_{j(i)} + \left(s_j - d_j \right) q_i \right)^-}{\left(1 + R/100 \right)^{\left(D_j - D_0 \right)}} \tag{3}$$

Availability penalty is equal to the net present value of the sum of the penalty costs for all parts in the system at each of the time steps after an inventory shortage. Availability penalty for a single part at a single time step is equal to the product of the penalty fee (p) and the quantity required. The quantity required is the sum of the current stock at the beginning of the time interval and the difference between the supply and demand for the number of instances of the part in the system.

While $t>0$, when any part becomes obsolete and its initial purchased quantity runs short and must be acquired again for a specified period in the future, a penalty cost u will be incurred if the part is unavailable from any other source. This cost may be due to loss of profit, loss of customer loyalty, or broken contractual agreements with customers. Component and system unavailable penalty cost (C_u) is given by (4).

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[5] Part resurrection refers to requests that manufacturers receive to restart manufacture of an obsolete part

$$C_u = \sum_{j=1}^{T} \frac{p_{su} I\left(\min_i\left(S_{j(i)} + \left(s_j - d_j\right)q_i\right) < 0\right)}{\left(1 + R/100\right)^{\left(D_j - D_0\right)}}$$ (4)

$$\text{where } I = \begin{cases} 1, & \text{if true} \\ 0, & \text{otherwise} \end{cases}$$

The equation for system unavailability penalty is the same for its availability penalty without summation for each part. The penalty is associated with the system versus individual components.

During the life cycle, $t>0$, the holding costs (part inventory and storage costs) incurred are given by C_{hc} in (5).

$$C_{hc} = \sum_{j=1}^{T} \sum_{i=1}^{N} \frac{h_i S_{j(i)} t_s}{\left(1 + R/100\right)^{\left(D_j - D_0\right)}}$$ (5)

Inventory costs include storage facility, labor, and maintenance fees. New and returned or remanufactured parts have equal holding cost rates per part. One assumption for the modified Teunter and Fortuin model is that remanufacturing cost is insignificant. Remanufacturing is defined as repair and re-qualification of a returned potentially defective part. Remanufacturing is assumed to happen immediately upon return of the product. For electronic parts, remanufacturing may be rare. Most components are disposed or replaced. To assume that remanufacturing cost is negligible is accurate.

Holding cost is the net present value of the sum of all holding costs for all parts at each time step. For an individual part at a specific time step, holding cost is equal to the product of the holding rate for that part, the stock quantity for that part at a specific time step, and the time step.

At the end of a system life, if spare parts remain, a removal cost C_{rc} is incurred. (6) gives the expression for removal cost.

$$C_{rc} = \sum_{i=1}^{N} \frac{r_i S_{T(i)}}{(1+R/100)^{(D_T-D_0)}} \tag{6}$$

The removal cost is unique compared to other costs, in that it can be positive or negative. It is calculated as the net present value of the sum of removal costs for all parts left over at $t=T$. The individual removal cost for each part is the product of the removal rate and the stock remaining. If a part becomes waste and must be disposed of, then the removal rate r is positive. However, if the part can be recycled or reused in other systems or salvaged the removal rate is negative.

These lifetime buy costs are summed into the function $g()$ in (7).

$$g(\ ) = \sum_{i=1}^{N} \left[\frac{c_i n_i}{(1+R/100)^{(D_i-D_0)}} + \frac{r_i S_{T(i)}}{(1+R/100)^{(D_T-D_0)}} \right]$$
$$+ \sum_{j=1}^{T} \frac{1}{(1+R/100)^{(D_j-D_0)}} \left[\begin{array}{c} p_{su}\left(S_{j(i)} + (s_j - d_j)q_i\right)^- \\ + \sum_{i=1}^{N} \left\{ p_i \left(S_{j(i)} + (s_j - d_j)q_i\right)^- + h_i S_{j(i)} t_s \right\} \end{array} \right] \tag{7}$$

where, $S_{j(i)} = d_{j(i)} = 0$ for $D_j < D_i$.

In (7), the costs that are outside of the time loop expressed by the summation over j, are not completely independent of time. Procurement cost is incurred upon obsolescence and is net present valued to a desired date. All procurement costs before obsolescence are not considered by the model. Procurement costs before obsolescence only shift the total cost, but will not change the calculation of the optimum quantities of parts to lifetime buy.

To supplement (7), (8)-(11) model the effects of equal run-out. Equal run-out is one possible cause of system unavailability. When a part in a system becomes

unavailable for any reason, the entire system becomes non-producible. All other parts are left unused in inventory. This effect is known as equal run-out or "matched sets." The variable $S_{j(i)}$ in (8) defines the inventory level for part i at the time step j. If the obsolescence date is after the current date for the part in question, the lifetime buy inventory level is zero. This indicates inventory before obsolescence are not considered in the model. As the time step advances, when the obsolescence data is either equal to or greater than the current date and before the current date plus one time step, then the inventory level is equal to the current stock minus the supply and demand for that part in that time period. This gives the inventory for the first time step after obsolescence occurs. Once obsolescence has occurred, the total inventory for each part and period is equal to the sum of the inventory of all previous time periods until the time in question. If the obsolescence date is before the current date, the inventory level is the current stock minus the sum of demand and supply for that part since obsolescence.

$$
S_{j(i)} = \begin{cases} n_i - \left(s_j - d_j\right)^+ q_i, & D_j \leq D_i < D_{j+1} \\ n_i - \sum_{k=j_i}^{j} \left(s_k - d_k\right)^+ q_i, & D_j > D_i \\ 0, & D_j < D_i \end{cases} \tag{8}
$$

The function $f_{j(i)}$ in (8) states the procurement state of part i at the time step j. If the current time step is either greater than or less than the part obsolescence date, procurement is equal to zero. However, procurement is incurred when the obsolescence date for the part is equal to or greater than the current time period but less than the next time period.

$$f_{j(i)} = \begin{cases} 1, & D_{j_i} \le D_i < D_{j_i+1} \\ 0, & D_j < D_i \ OR \ D_j > D_i \end{cases} \tag{9}$$

Equation (10) gives the cost incurred at the last time step in the lifecycle, which include the disposal or residual costs.

$$g_T\left(S_{j(1)},...,S_{j(i)}\right) = \sum_{k=1}^{i}\left(\frac{h_k}{12} + f_{T(k)}\right)y_k + a \underset{s_T,d_T}{E}\left[\sum_{k=1}^{i}\left\{\begin{array}{l} p_i\left(S_{T(k)} + \left(s_T - d_T\right)q_k\right)^- \\ + r_k\left(S_{T(k)} + \left(s_T - d_T\right)q_k\right)^+ \end{array}\right\}\right] \tag{10}$$

For all intermediate time periods j within the product lifecycle, where $j \in \{1, \dots T\text{-}1\}$, the sustainment costs are represented in (11).

$$g_j\left(S_{j(1)},...,S_{j(i)}\right) = \sum_{k=1}^{i}\left(\frac{h_k}{12} + f_{j(k)}\right)y_k + a \underset{s_j,d_j}{E}\left[\begin{array}{l} \sum_{k=1}^{i}p_i\left(S_{j(k)} + \left(s_j - d_j\right)q_k\right)^- \\ + g_{j+1}\left(S_{j+1(1)}...S_{j+1(i)}\right) \end{array}\right] \tag{11}$$

Mathematically, sustainment cost minimization is represented by (12). The goal is to minimize the lifecycle cost for all parts 1 through i throughout the entire product lifecycle.

$$\min_{n_i \ge 0,} g_1\left(n_1,...,n_i\right) \tag{12}$$

The modified Teunter and Fortuin model and the original have subtle but important differences. The modified model has an additional system unavailability penalty that was not in the original model. Rather than calculating lifecycle cost on a part-by-part basis, the modified expression calculates the lifecycle cost for the whole system. Solutions are generated stochastically to account for the uncertainties in all variables in the modified model.

2.3 Life of Type Evaluation (LOTE) Tool Overview

The Life of Type Evaluation (LOTE) Tool was created to transform the modified Teunter and Fortuin model into a usable form. The LOTE application is capable of calculating lifetime buy quantities and bridge buy quantities. The LOTE software uses Monte Carlo analysis to represent the stochastic nature of the lifetime buy problem. The uncertainties lie with the forecasted demand, part obsolescence date, and penalty costs. As mentioned in the introductory chapter, the demand forecast aspect of this the lifetime buy problem is out of the scope of this thesis. It is assumed that demand forecasts are supplied from another entity. Likewise, parts obsolescence dates are not always certain. System unavailability penalty and system availability penalty are difficult to predict and at times hard to quantify. The uncertainties involved with part demand, obsolescence dates, and penalty costs justify the stochastic nature of the solution.

Predicting parts obsolescence dates is a field of research on its own. There are programs available on the market that monitor all parts availabilities (e.g. PartMiner, Information Handling Systems, Q-Tech, Silicon Expert, Arrow Electronic) and their current stage in their product lifecycle [16]. Part-specific obsolescence forecasts from these tools are used as inputs to the LOTE analysis tool.

In the case of demand, product-specific demand schedules are used and augmented by assumed demand uncertainties.

2.4 Searching for Lifecycle Cost Minimum

The optimal lifetime buy function (11)-(12) analyzed is relatively simple to calculate in concept. It has only one global minimum assuming the function is linear[6]. All contributing costs (procurement, holding, disposal, and penalty) are considered either monotonically increasing or decreasing functions. Monotone functions are those that preserve the order given [14]. Increasing monotonic functions are those to where if $x \leq y$, then $f(x) \leq f(y)$ [14]. Decreasing monotonic functions are those where if $x \leq y$, then $f(x) \geq f(y)$ [14], the given order is reversed. Procurement and holding costs are considered monotonically increasing functions. With increased quantities of lifetime buy parts, procurement and holding costs both increase. Depending on the disposal method, disposal cost can be either a monotonically increasing or decreasing function. If the remaining parts are salvaged and/or recycled, the disposal cost decreases with part quantity. However, if the remaining parts are disposed of as waste, the cost increases with party quantity. Lastly, penalty (system unavailability and availability) is monotonically decreasing. With more parts, penalty increases.

When these costs are added together, the result could be monotonically increasing, decreasing, or a minima or maxima. If the solution is increasing with party quantity, the optimum lifetime buy quantity or lowest lifecycle cost is when the quantity equals zero, where no parts are purchased. If the solution is decreasing with part quantity, the optimum lifetime buy quantity or lowest lifecycle cost is when the quantity is infinity, where there is no chance of incurring penalties. However, when procurement, holding, disposal, and penalties are all accounted for, there is an

---

[6] It has not been proven that the function is linear. However results are local minimums. The brute force method mentioned in Section 2.7 demonstrated local minimum. The gradient search algorithm currently used has been tested against the brute force method. The gradient search algorithm has been programmed to find the local minimum using first and second derivatives.

interaction between the increasing and decreasing functions. The resulting function is no longer monotonically increasing or decreasing, but both. Therefore, there is one single lifecycle cost minima that result from the interacting functions.

Knowing that the solution is the only minima, simplifies the solution search. The LOTE tool varies the lifetime buy quantity from 0 to m and calculates the lifecycle cost at each of these quantities. LOTE completes its search once it finds the lifetime buy quantity that gives the minimum cost. The minimum lifecycle cost is found at m-1. For each of the lifecycle cost calculations, the demand and penalties are sampled from distributions using Monte Carlo analysis. The distribution values are used to find a mean lifecycle cost value at the lowest non-negative lifetime buy quantity where the slope of the lifecycle cost curve is positive or rounded up. One important point is that once the distributions demand, obsolescence date, and penalty are determined, they are assumed to be independent of time.

2.5 LOTE Sequence of Events

Given product component and production information, LOTE arranges all parts in the system in order of increasing obsolescence date. Using the Monte Carlo distribution values, it calculates the optimum lifetime buy quantities and the corresponding minimum lifecycle cost. The sequence is pictorially represented in Figure 3. LOTE starts with the first part to become obsolete and assumes there is no future view of the system past the current time. It assumes either all parts in the future do not go obsolete or lifetime buys for all future parts are perfect and result in a constant increase in overall cost to the system. Using this assumption and the Monte

Carlo sampling of input data distributions in the modified Teunter and Fortuin model, LOTE calculates the lifetime buy quantity corresponding to the minimum lifecycle cost for the first part.

The second part to go obsolete undergoes the same analysis with the same assumptions and one additional factor. It also considers the previous part's obsolescence date and lifetime buy quantity. If part one runs out before the end of the system lifecycle, part two will make a more conservative lifetime buy than if part one was not considered. The subsequent parts follow this same procedure to determine lifetime buy quantities and lifecycle costs. Ideally these steps are embedded within another Monte Carlo loop for the obsolescence dates. However, currently the LOTE tool does not offer this feature.
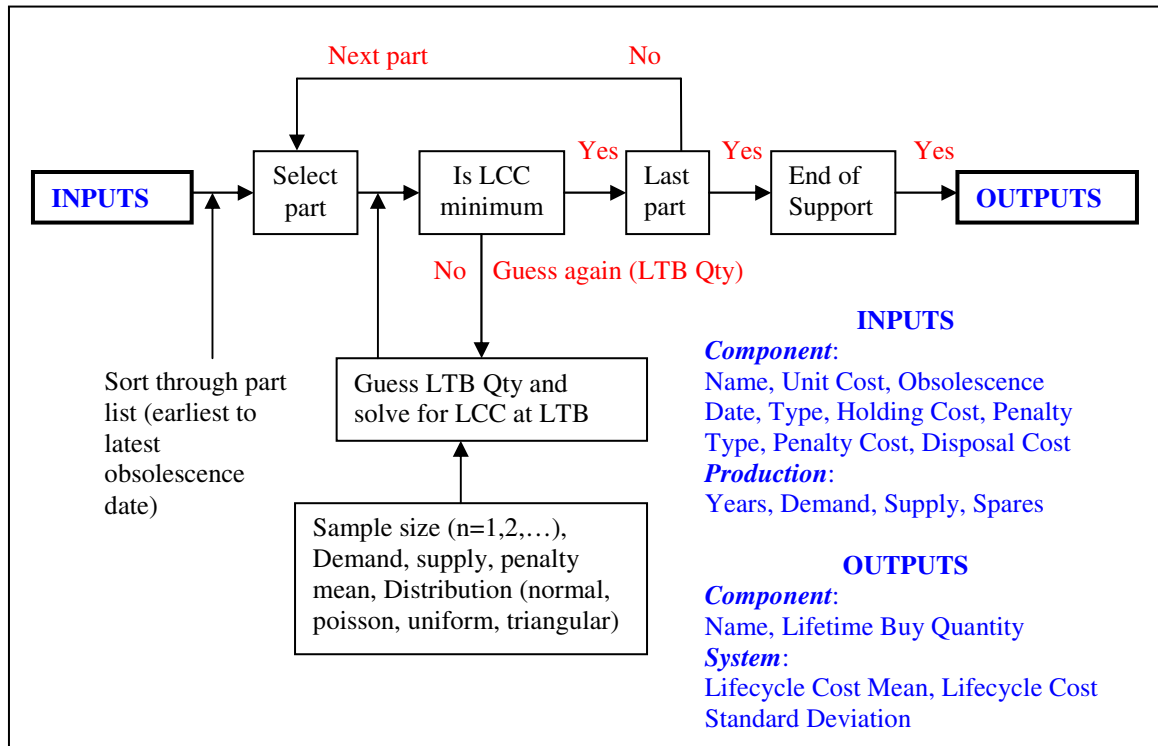

Figure 3. Life of Type Evaluation tool sequence of events.

The solution set found from this model does not guarantee a global minimum. It is a non-iterative process that offers incremental practical solutions, i.e., this is an emulation of a real product management process that optimizes based on current state of the product and an idealized assumption of the future. To find the global minimum, the process above would only represent the first iteration. The lifetime buy quantities determined for each part in the first iteration would be used as the assumed future lifetime buy quantities for the parts in the second iteration. The solution would be iterated until the solutions converge and the lifetime buy quantities stop changing. However, it has not been shown that an iterative process like the one postulated gives the global minimum solution, and that the solution has a specific meaning. The iterative approach does not offer a practical solution to management, as the non-iterative solution is the best guess solution given the situation. However, this iterative solution may provide good advice for budget planning.

2.6 Demand Variation

The Teunter and Fortuin model assumes a single demand and supply value over the entire span of the project lifetime, which is unrealistic. In fact, based on the Infrastructure Base Station demand profile from Motorola, demand profiles follow the lifecycle profile more like the one shown in Figure 4.

Demand profile makes a significant difference in the optimum solution as shown by the results in Chapter 3. Therefore, to provide results as accurate as possible the data needs to be as close to the actual situation as possible and variable demands must be modeled
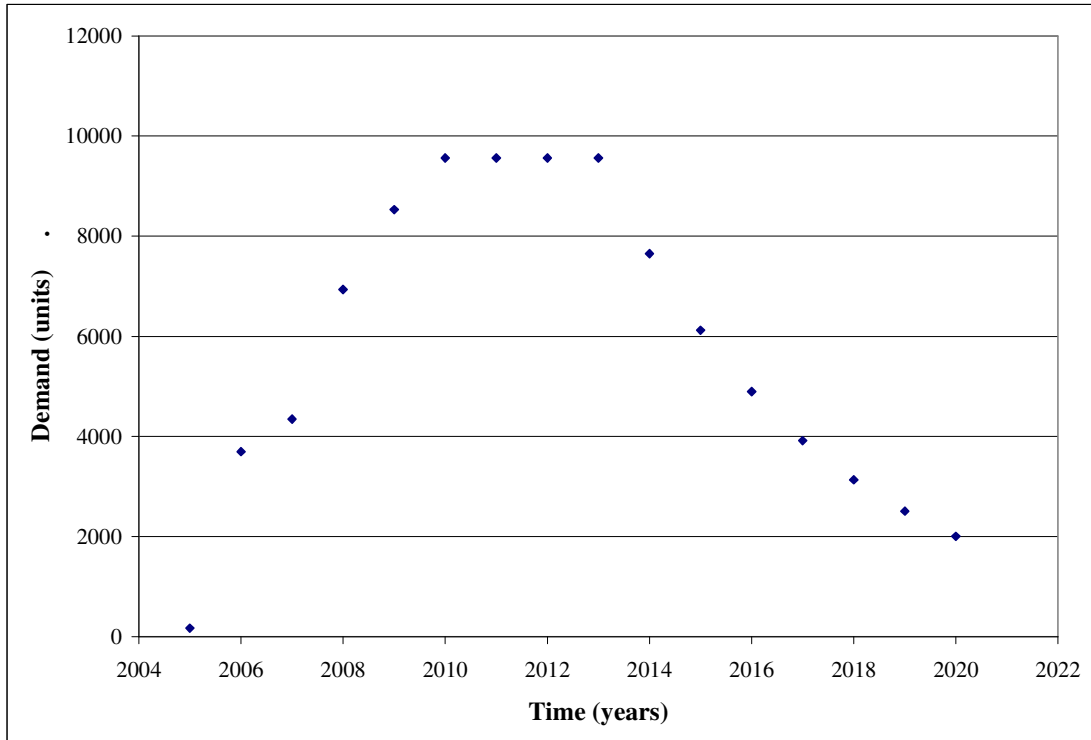
Figure 4. Production profile for Motorola Infrastructure Base Station.

2.7 Optimization with Gradient Search

A key component to the success of LOTE is the data analysis speed and required memory space. The search algorithm function in LOTE requires the majority of time and memory. The software must find the minimum lifecycle cost (LCC) associated with making the appropriate lifetime buys for all obsolete parts to sustain the system until its end of life without penalty of over or under buying.

LOTE, in its original version (version 1.0) solved for lifecycle costs in a very simple and time consuming way. First, it requested users to input a range of life time buy quantities within which to search. Users provided an M minimum ("Smallest M"), M maximum ("Largest M") and M increment size ("Step size") through the "System Setup" window; where M represents the LTB quantity. Starting at the

minimum LTB quantity, M minimum, LOTE calculates the LCC associated with that quantity. The application increments in the user stated step size, through the range of M values the user inputs and stops at the M maximum. For each M value in the range, LOTE solves and saves just the LCC at that quantity if Monte Carlo analysis is turned Off. If Monte Carlo analysis is activated, at each M value in the specified range, the mean, standard deviation, maximum, and minimum LCC associated with that M value is saved in an array. From there, the program searches through the saved lifecycle cost array for the lowest cost.

In the original LOTE, a search mechanism compares the solved LCC at each M value in the range against the next, from M minimum to M maximum. After searching through the entire array, the software returns the LTB quantity that yields the minimum LCC, along with the cost and the standard deviation. This process is done for each component in the component list.

The solution process described above is a brute-force method. Assuming a system contains 10 parts, all of which become obsolete during the analysis period. Without making changes to the default LTB quantity range, the search will iterate from LTB quantities of 0 to 100 at step sizes of 1. Activate the Monte Carlo analysis. The array that saves all of the data will contain 4 values for each M value (LCC minimum, maximum, mean, and standard deviation). There are 400 values saved for each component. For the assumed 10 part system 4,000 values are saved in the array. LOTE's search through 1,000 values to find the 10 LCC for the 10 components. This simple example shows that conducting the lifetime buy analysis was no small task for

LOTE. Real systems contain hundreds of components and will require large amounts of time for analysis and memory space to save the data.

To reduce run time and memory usage, a gradient search method was introduced. Gradient search finds the slopes of the function analyzed at its minimum and maximum x-axis values and predicts, based on the steepness of the slopes, where the minimum y-axis value is most likely to occur using first and second derivatives. After an initial guess, usually very close to the solution, the gradient search samples values around the guess to find the exact minimum y-value. Instead of the brute-force method that could require up to M maximum guesses, gradient search will find a solution within 3 to 4 guesses. The run time and memory usage of the gradient search method is considerably reduced compared to the brute-force method.
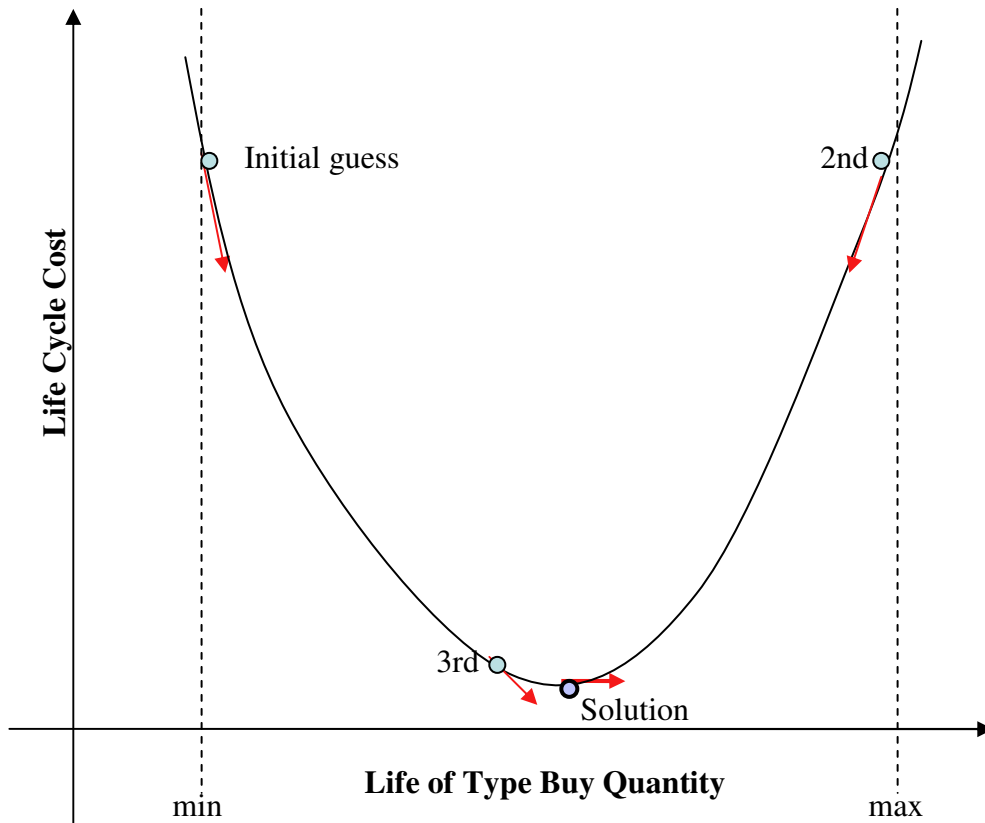

Figure 5. Gradient search procedure (Begin search at initial guess, progress through 2nd and 3rd guesses to narrow down solution using slopes and lifecycle costs values at 2nd and 3rd guesses).

An existing gradient search subroutine from the University of South Carolina was incorporated into the LOTE code [24].

Ultimately, the gradient search allows users to control the range of the search similar to the brute-force method. Dissimilarly, the gradient search is set at a default step size of one. It is more precise without additional cost to run-time and memory space. Each search starts at an initial guess equal to the demand value to minimize the number of search steps. Also, the search tolerance is set to the ones as oppose to smaller sizes on the thousandths or hundredths scale. Since lifetime buy quantities are only in integers, the accuracy that the gradient search algorithm offers is unnecessary.

2.8 Refresh Insertion

The Teunter and Fortuin model was created for lifetime buys. In real cases refreshes or upgrades to existing systems must be considered. Design refreshes replace obsolete parts with non-obsolete parts and perform required re-qualification activities. In the case of refreshes, if the obsolescence event is before the refresh, a bridge buy is made to the refresh date (where the part is replaced), and lifetime buys are made for obsolescence events that occur after the refresh. The sequence of events with a refresh is very similar to the sequence for lifetime buy; with one additional loop for refreshes after all other loops have been processed (Figure 6).

Given component, production, and refresh information, LOTE sorts all refresh dates in ascending order. For the first refresh period, all parts with obsolescence dates within that time frame are arranged in increasing obsolescence dates. For each part,

LOTE searches for the minimum LCC and the associated bridge buy quantity using the demand, supply, and penalty distribution. LOTE loops the entire parts list until it has calculated the optimal bridge buy quantity for all parts within that refresh time period. It then, loops to the time period after the refresh (or if there are multiple refreshes, to the next refresh period) and does the same analysis. In this second time frame, all parts that were purchased before the new refresh date have their lifetimes reset based on the type of part, i.e., LOTE assumes that all parts that become obsolete prior to the refresh are replaced at the refresh. Any parts that became obsolete before the refresh date, is listed as a new replacement part after the refresh with the same part number and an additional dash and number to indicate that it is a replacement. The replacement part is treated like any original part, and may become obsolete after the refresh and bridge bought.
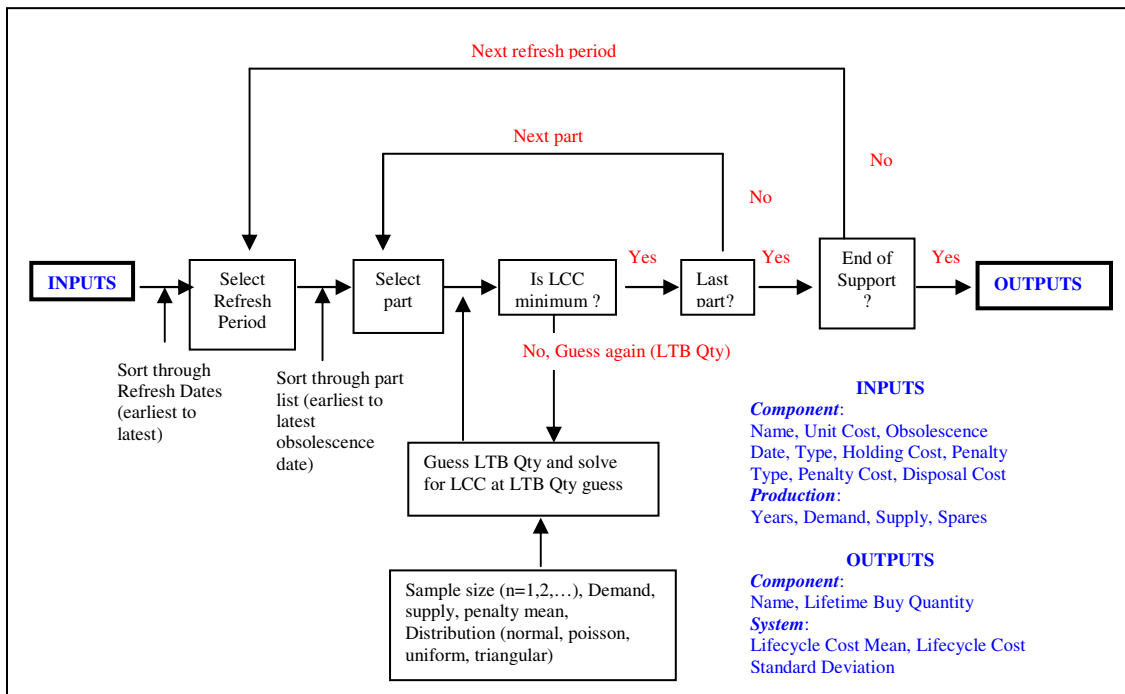

Figure 6. Life of Type Evaluation Tool sequence of events with refresh insertion.

It is often the case at re-designs that engineers will look ahead a predetermined time period for parts that are expected to become obsolete and redesign those parts all at once. This predetermined time is known as the look-ahead time. With the re-design date insertion, LOTE offers users the option to insert a look-ahead time in years. LOTE adds this quantity to the designated redesign dates and essentially push the redesign date ahead by the look-ahead years. All other analyses are the same.

2.9 Summary

The Life of Type Evaluation Tool (LOTE) is an extended version of the Teunter and Fortuin model. LOTE is a practical transformation of the Teunter and Fortuin model with additional features that allow it to be applied to electronic part lifetime buy management problems. LOTE takes into account all cost factors that contribute to procurement lifecycle cost (procurement, inventory, disposal, penalties) and weighs the positives and negatives to solve for a lifetime buy quantity that will result in the lowest lifecycle cost. LOTE can handle much more complex problems than the original Teunter and Fortuin model. LOTE solves for lifecycle cost for an entire multi-part system sequentially and coupled rather than one part at a time independent of other part lifetime buy quantities. LOTE also accounts for uncertainties in the demand and penalty inputs through a variety of distributions (normal, uniform, Poisson, triangular) and variations in demand. LOTE also allows users to define re-design dates and look-ahead times for bridge buys in addition to lifetime buys.

Chapter 3 presents results from LOTE analyses of a Motorola product. The chapter starts with simple calculations for cost to demonstrate the sequence of

calculations LOTE employs. Chapter 3 then shows how changing cost and date variables affect the solution (lifecycle cost and lifetime buy quantity) on a single part case. The chapter is concluded with a complete analysis of a Motorola case.

Chapter 3: Lifetime Buy Optimization Case Study

This chapter describes lifetime buy optimization analysis results generated using the LOTE tool. This chapter begins with simple calculation examples that demonstrate the logic LOTE uses to make its calculations. The initial demonstration calculations are made for single-part analysis over a period of time without any demand distributions. Increasing in complexity, calculations are made for multiple parts without demand distributions. The sections that follow give results of a single part situation with demand distributions using Monte Carlo analysis and sensitivities analysis of variables (procurement, holding, disposal, obsolescence date). Lastly, the results from analysis of a Motorola Infrastructure Base Station are presented. These results are based on input from Motorola and directly relates to a product currently in being produced and supported by Motorola. These examples show LOTE's capabilities as a practical tool to solve real industry lifetime buy and bridge buy management problems.

3.1 LOTE Cost Assumptions

The following assumptions are made in the LOTE cost models:

- Analysis start date is assumed to be on the first day of the year (e.g., 2000 = January 1, 2000)
- Analysis end date is assumed to be on the last day of the year (e.g., 2010 = December 31, 2010).
- Yearly demand is drawn on the last day of the year (i.e., demand is drawn from inventory on December 31)
- Obsolescence occurs on the first day of the year (e.g., 2002 = January 1, 2002)
- Lifetime and bridge buys are assume to take place on the obsolescence date
- Holding costs are incurred on the first day of the year in advance for all parts held that year (e.g., 2002 = January 1, 2002)

LOTE computes costs associated with each part. These costs are used to compare different lifetime (or bridge) buy quantities. The quantity that minimizes these costs is selected by LOTE. LOTE only computes the costs incurred by a part from its obsolescence date to the end of support for the product that it is in. Therefore, the costs computed for a part by LOTE include:

- Procurement of lifetime (or bridge) buy quantities
- Storage (holding) costs associated with the lifetime (or bridge) buy inventories
- Part-specific availability penalties (incurred when the inventory runs out and the part can still be procured, but at a different cost)
- System-specific unavailability penalties (incurred when the inventory runs out and the part cannot be procured)
- Disposal costs for excess inventory
- Financial costs associated with all of the above items (i.e., cost of money)

Other costs associated with the part or system are not included in the LOTE analysis. For example, the costs computed by LOTE do NOT include:

- Cost of procuring parts prior to their obsolescence date
- Cost of obsolescence case resolution activities (besides the actual cost of the lifetime or bridge buys as detailed above)
- Costs of assembling, qualifying or testing systems

3.2.1 Single Part Cost Calculations at Demand

This section demonstrates the calculations for a very simple case. Consider a very simple example with the following inputs:

Part name = p2
Part unit cost = $5/part
Obsolescence date = 2002 (January 1, 2002)
Analysis start date = 2000 (January 1, 2000)
End of support date = 2010 (December 31, 2010)

Demand = 20 parts/year (No uncertainty)
Discount rate = 0%
Holding rate = $0 (inventory cost)
Disposal cost = $0

1. Using the data above, the LOTE cost is computed as:

Quantity needed at lifetime buy = (2010-2002+1 years) (20 parts/year) =
= 180 parts
LOTE cost = procurement cost + holding cost + penalty cost + disposal cost
= (180 parts) ($5 /part) + $0 + $0 + $0 = $900

2. Now change the discount rate to 10% (and set the discount rate base year to

January 1, 2000):

$$\text{LOTE cost} = \frac{(180)(\$5)}{(1+0.1)^{(2002-2000)}} = \$743.80$$

3. Set the discount rate back to 0% and set the following (in order to include storage

costs):

Holding rate = $1/part/year (cost specifically for the part)
LOTE cost = procurement cost + holding cost + penalty cost + disposal cost
= (180 parts) ($5 /part)
+ (180 + 160 + 140 + 120 + 100 + 80 + 60 + 40 + 20) part year
x ($1/part/year)
+ $0 + $0
= $1800

The result of the above calculation is in year 2000 dollars. The above calculation

also assumes that the 20 part demand per year is consumed on the last day of the year.

4. Now change the discount rate to 10% (and set the discount rate base year to

January 1, 2000) again:

$$\text{LOTE cost} = \frac{(180)(\$5)}{(1+0.1)^{(2002-2000)}} + \begin{bmatrix} \dfrac{(180)(\$1)}{(1+0.1)^{(2002-2000+1)}} + \dfrac{(160)(\$1)}{(1+0.1)^{(2003-2000+1)}} + \dfrac{(140)(\$1)}{(1+0.1)^{(2004-2000+1)}} \\[2mm] + \dfrac{(120)(\$1)}{(1+0.1)^{(2005-2000+1)}} + \dfrac{(100)(\$1)}{(1+0.1)^{(2006-2000+1)}} + \dfrac{(80)(\$1)}{(1+0.1)^{(2007-2000+1)}} \\[2mm] + \dfrac{(60)(\$1)}{(1+0.1)^{(2008-2000+1)}} + \dfrac{(40)(\$1)}{(1+0.1)^{(2009-2000+1)}} + \dfrac{(20)(\$1)}{(1+0.1)^{(2010-2000+1)}} \end{bmatrix} = $$

$$= \$1279.50$$

This assumes that the holding cost is charged on the last day of the year, i.e., "$1"
is added to the date difference in the NPV cost calculation.

3.2.2 Single Part Cost Calculations with Monte Carlo Analysis

The simple calculations in Section 3.2.1 are done assuming no uncertainties in the
demand (it's always 20 parts/year), the obsolescence date, or the end of support date.
When these uncertainties are introduced, a calculation like the one above has to be
done with a Monte Carlo sampling approach and a distribution of costs results for a
particular lifetime buy size.

In the cases above, there are no penalties because 180 is always exactly the right
number to buy. Consider the following case:

1. Assume that 170 parts are purchased at the lifetime buy (10 less than the demand
   requirement)

   System unavailability penalty = $1500 (assumes that the part is unavailable once
   the inventory runs out)

   LOTE cost = procurement cost + holding cost + penalty cost + disposal cost =

$$\frac{(170)(\$5)}{(1+0.1)^{(2002-2000)}} + \begin{bmatrix} \dfrac{(170)(\$1)}{(1+0.1)^{(2002-2000+1)}} + \dfrac{(150)(\$1)}{(1+0.1)^{(2003-2000+1)}} + \dfrac{(130)(\$1)}{(1+0.1)^{(2004-2000+1)}} \\[2mm] + \dfrac{(110)(\$1)}{(1+0.1)^{(2005-2000+1)}} + \dfrac{(90)(\$1)}{(1+0.1)^{(2006-2000+1)}} + \dfrac{(70)(\$1)}{(1+0.1)^{(2007-2000+1)}} \\[2mm] + \dfrac{(50)(\$1)}{(1+0.1)^{(2008-2000+1)}} + \dfrac{(30)(\$1)}{(1+0.1)^{(2009-2000+1)}} + \dfrac{(10)(\$1)}{(1+0.1)^{(2010-2000+1)}} \end{bmatrix} + \frac{(10)(\$1500)}{(1+0.1)^{(2010-2000+1)}} + \$0$$

$$= \$6447.99$$

2. Assume that 170 parts are purchased at the lifetime buy (10 less than the demand requirement).

   System availability penalty = \$50 (the part is available after the inventory runs out but for \$50 each).

   LOTE cost = procurement cost + holding cost + penalty cost + disposal cost =

$$\frac{(170)(\$5)}{(1+0.1)^{(2002-2000)}} + \left[\begin{array}{l} \dfrac{(170)(\$1)}{(1+0.1)^{(2002-2000+1)}} + \dfrac{(150)(\$1)}{(1+0.1)^{(2003-2000+1)}} + \dfrac{(130)(\$1)}{(1+0.1)^{(2004-2000+1)}} \\[2ex] + \dfrac{(110)(\$1)}{(1+0.1)^{(2005-2000+1)}} + \dfrac{(90)(\$1)}{(1+0.1)^{(2006-2000+1)}} + \dfrac{(70)(\$1)}{(1+0.1)^{(2007-2000+1)}} \\[2ex] + \dfrac{(50)(\$1)}{(1+0.1)^{(2008-2000+1)}} + \dfrac{(30)(\$1)}{(1+0.1)^{(2009-2000+1)}} + \dfrac{(10)(\$1)}{(1+0.1)^{(20010-2000+1)}} \end{array} \right] + \frac{(10)(\$50)}{(1+0.1)^{(2010-2000+1)}} + \$0$$

$$= \$1365.83$$

3. Assume that 190 parts are purchased at the lifetime buy (10 more than the demand requirement).

   Disposal cost = -\$2.00/part (assume the part is recycled and used on another product)

   LOTE cost = procurement cost + inventory cost + penalty + disposal =

$$\frac{(190)(\$5)}{(1+0.1)^{(2002-2000)}} + \left[\begin{array}{l} \dfrac{(190)(\$1)}{(1+0.1)^{(2002-2000+1)}} + \dfrac{(170)(\$1)}{(1+0.1)^{(2003-2000+1)}} + \dfrac{(150)(\$1)}{(1+0.1)^{(2004-2000+1)}} \\[2ex] + \dfrac{(130)(\$1)}{(1+0.1)^{(2005-2000+1)}} + \dfrac{(110)(\$1)}{(1+0.1)^{(2006-2000+1)}} + \dfrac{(90)(\$1)}{(1+0.1)^{(2007-2000+1)}} \\[2ex] + \dfrac{(70)(\$1)}{(1+0.1)^{(2008-2000+1)}} + \dfrac{(50)(\$1)}{(1+0.1)^{(2009-2000+1)}} + \dfrac{(30)(\$1)}{(1+0.1)^{(2010-2000+1)}} \end{array} \right] + \$0 + \frac{(10)(\$-2)}{(1+0.1)^{(2010-2000+1)}}$$

$$= \$1361.41$$

4. Assume a refresh date of 2005.

   LOTE cost = procurement cost + inventory cost + penalty cost + disposal cost

$$= \frac{(80)(\$5)}{(1+0.1)^{(2002-2000)}} + \left[\begin{array}{l} \dfrac{(80)(\$1)}{(1+0.1)^{(2002-2000+1)}} + \dfrac{(60)(\$1)}{(1+0.1)^{(2003-2000+1)}} + \dfrac{(40)(\$1)}{(1+0.1)^{(2004-2000+1)}} \\[2ex] + \dfrac{(120)(\$1)}{(1+0.1)^{(2005-2000+1)}} \end{array} \right] + \$0 + \$0$$

= $467.79

3.2.3 Multiple Parts Cost Calculations without Monte Carlo Analysis

When multiple parts are included in the analysis, the costs for each part are

calculated as in the examples in Sections 3.2.1 and 3.2.2 and the costs for the parts are

accumulated in analysis order (earliest to latest obsolescence date).   These

calculations are done by the LOTE tool rather than by hand.

For example, start with example 3 in Section 3.2.1, in this case part p2 by itself costs

$1800. Now include a second part p3 in the analysis, where

    Part name = p3
    Part cost = $10/part
    Obsolescence date = January 1, 2007

    Demand = 20 parts/year (No uncertainty)
    Discount rate = 0%
    Holding rate = $0.3/year (inventory cost)
    Penalty cost = $0
    Disposal cost = $0

Quantity needed at lifetime buy for p3 = (2010-2007)years x (20 parts/year)
                                                = 80 parts
LOTE cost (p3 alone) = (80 parts)($10 /part) + (80 + 60 + 40 + 20)years x ($0.3/year)
                        = $860

If LOTE is run for parts p2 and p3 at the same time at the specifications listed above

and without Monte Carlo sampling, the output in Figure 7 is obtained. The LCC Cost

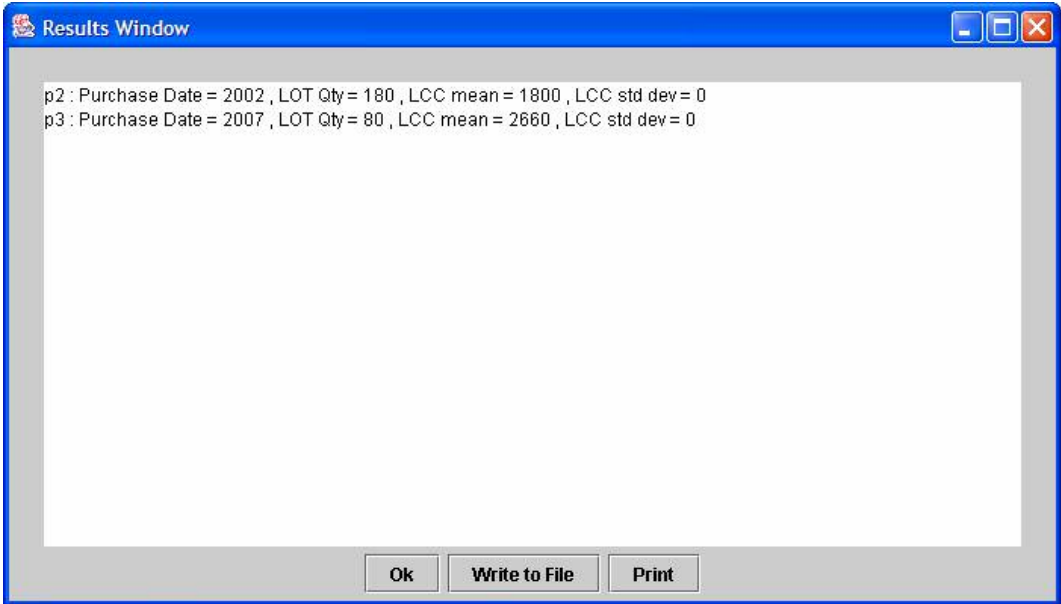of p3 is the cumulative of p2 and p3 which is $1800 + $860 = $2660.

Figure 7. Multi-part cost results.

3.3 Single Part Motorola Infrastructure Base Station Case Background

Using the LOTE software for a real product case study provides bountiful insight on the lifetime buy issue. The Motorola Infrastructure Base Station is a commercial off-the-shelf RF base station communications system. The Infrastructure Base Station program provides a radio frequency hardware platform for a variety for systems and communication modes. It also replaces several older base station products that Motorola offered. Over its 16 years planned manufacture and sustainment lifetime, more than 115,000 systems will be manufactured. It is comprised of 1218 components total, of which 249 are unique components. Its production period started in 2005 and is planned to complete in 2020. The end of support date for this product is at the end of the year in 2020. The forecasted demand for each production year is depicted in Figure 8. Figure 9 graphically shows the number of forecasted electronic part obsolescence events throughout the system lifetime.
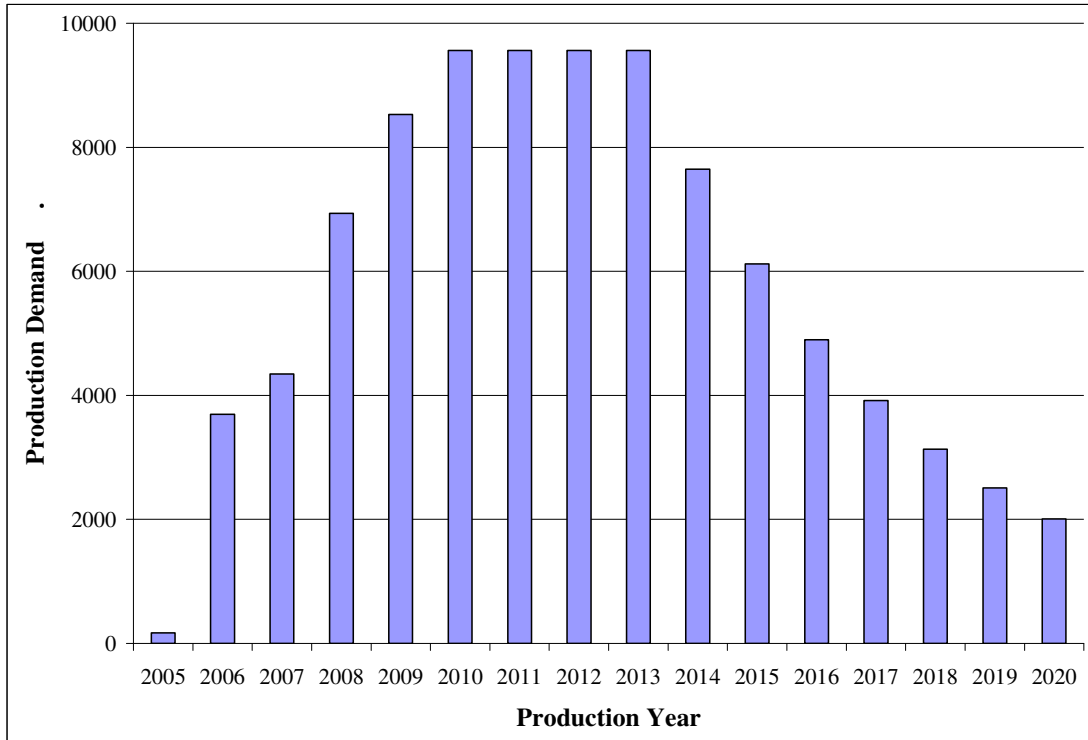
Figure 8. Motorola Infrastructure Base Station production information.

The Infrastructure Base Station program data was previously analyzed using the Mitigation of Obsolescence Cost Analysis (MOCA) software at the University of Maryland. MOCA results were instrumental in recommending an optimum refresh plan to Motorola. The recommended optimum refresh plan was a single refresh in the year 2011. As a continuation of the MOCA study, the same data along with the MOCA recommendation to this case study are used in LOTE.
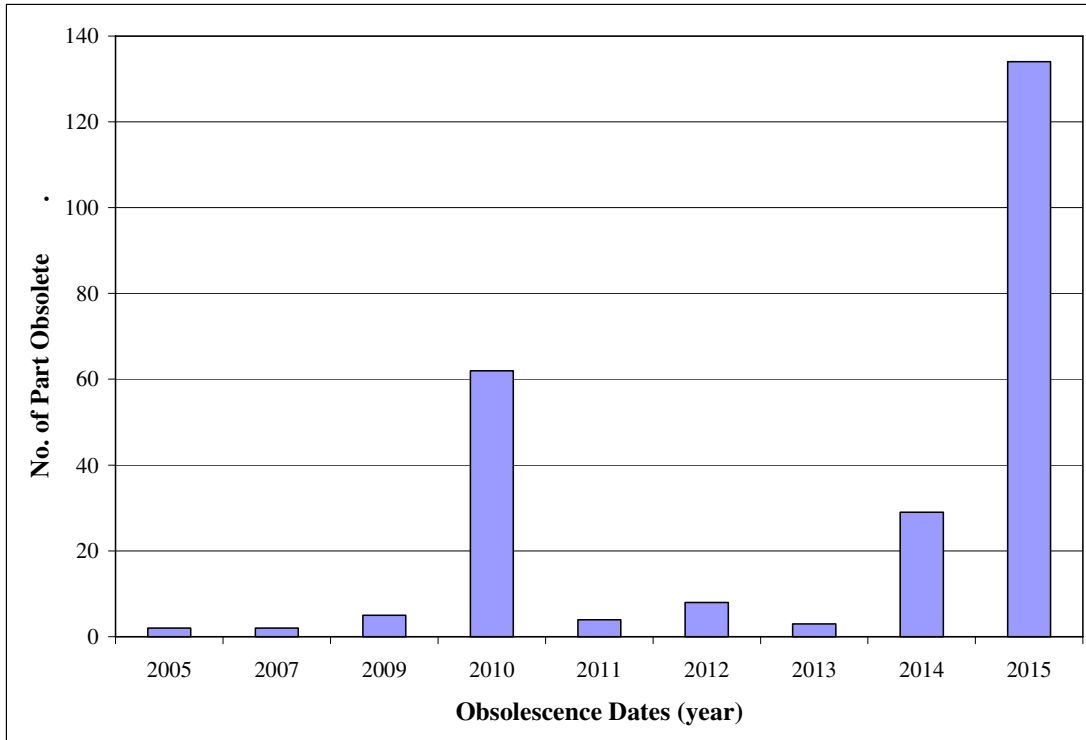
Figure 9. Number of obsolete parts vs. obsolescence date.

3.3.1 Single Part Case

Before analyzing the entire Infrastructure Base Station, an analysis of a single part in the Infrastructure Base Station was undertaken. In order to understand the complexities of the interacting variables, sensitivity analyses were conducted by varying the values of the contributing variables: system unavailability penalty, system availability penalty, holding rate, and disposal rate. A sensitivity analysis was conducted with each individual variable by varying the variable in question while other variables remained constant. These variables behaviors were also analyzed for various demand profiles and at different part obsolescence dates. Using the original production (demand) information provided by Motorola, the total demand quantity for the entire system was used to create constant, increasing, decreasing, increasing plateau, and decreasing plateau demand profiles over time all with the same total

44

demand quantity as the original data. To simplify the problem, only one part from the

Motorola bill of materials was analyzed in the sensitivity analysis[7] (Table 1).

Part Name	Quantity	Cost/Unit	Obsolescence Date	Part Type
4885061 Y01	2	0.048	2005	Diode

Table 1. Single part analysis part information.

The default settings on LOTE and the variable variations for the sensitivity

analysis are listed in Table 2.

Variables	Default	Vary System Unavailability Cost	Vary System Availability Cost	Vary Holding Cost	Vary Disposal Cost
System Unavailability Cost (per unit)	ON $1,500	ON $1 $1500 $10,000 $50,000 $1,000,000	Default	Default	Default
System Availability Cost (per unit)	OFF $50	Default	ON $5 $50 $500 $5,000	Default	Default
Holding Cost (per unit)	$0.20	Default	Default	$0.20 $1 $10 $100 $1,000	Default
Disposal Cost (per unit)	$0	Default	Default	Default	$0 $0.10 $1 $10 $100 $1,000

Table 2. Variables and settings changed for sensitivity analysis.

The multiple demand profiles tested are graphed in Figure 10.

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[7] The part used in the single part sensitivity analysis is the first part to go obsolete from the RF Base Station. All data for this part was provided by Motorola, along with the original demand profile over time.
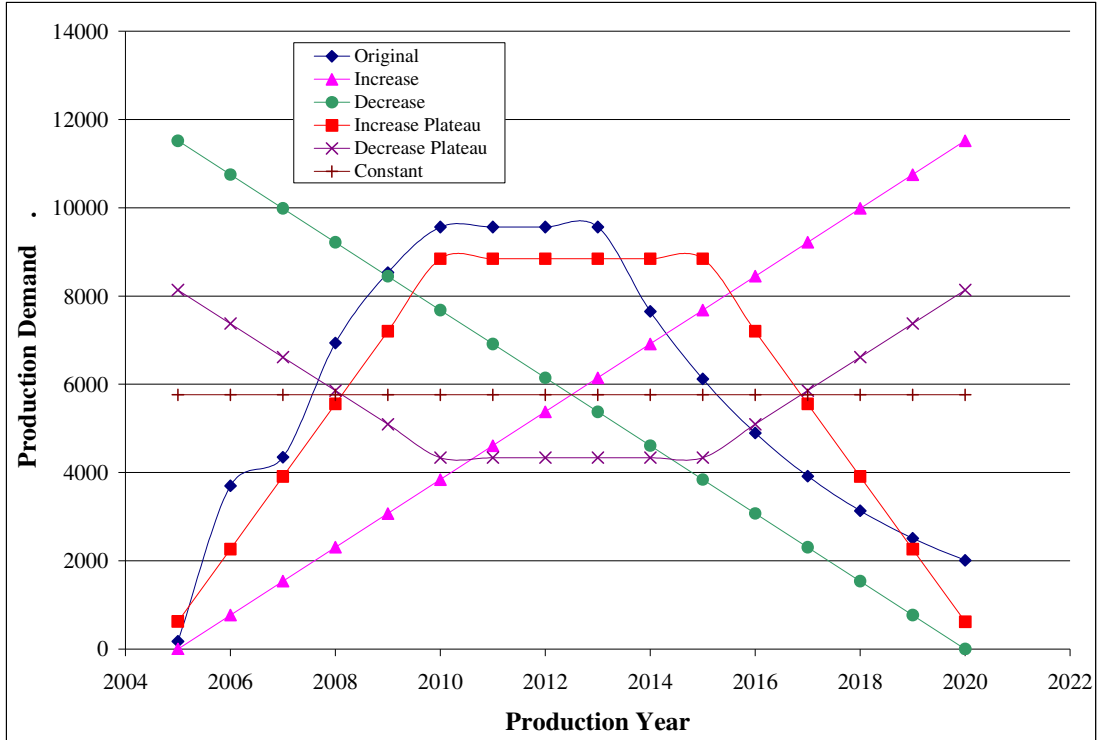
Figure 10. Production profiles tested in sensitivity analysis

3.3.2 Motorola Single-Part Case Study Results

All LOTE calculations are made with the Monte Carlo function turned ON. The sample size is set at 1,000 samples and the distribution type is set at Poisson distribution. All solutions generated at the expected demand quantity are referred to as the "demand solution," while solutions generated using the Monte Carlo Multi-Part Analysis option in LOTE are referred to as the "lifetime buy solution."

Table 3 gives the results for the single-part case study with the default data, with obsolescence in 2005 (a Motorola provided obsolescence date for the part) and using the original Motorola demand profile. Table 3 is only used as an example of the results.

Graphical representations of the results plot the ratio of either lifetime buy quantity (LTB Qty) over the expected demand quantity and lifecycle cost at the lifetime buy quantity (LCC) over the lifecycle cost at the expected demand quantity. These ratios standardize the results to compare lifetime buy quantities and lifecycle costs for different demand profiles.

$$\text{Lifetime Buy Ratio (LTB Ratio)} = \frac{\text{Optimum Lifetime Buy Quantity}}{\text{Lifetime Buy Quantity at Expected Demand}}$$

$$(13)$$

$$\text{LifeCycle Cost Ratio (LCC Ratio)} = \frac{\text{Minimum LifeCycle Cost at Optimum LTB Quantity}}{\text{LifeCycle Cost at Expected Demand LTB Quantity}}$$

$$(14)$$

When the lifetime buy quantity ratio (13) equals one at a given variable setting, demand profile, and part obsolescence date, the optimum solution (lowest lifecycle cost) for the system wants to purchase the same quantity of parts as at demand for that production profile, part obsolescence year, and variable setting. If the lifetime buy ratio is greater than one, the optimum solution (lowest lifecycle cost) for the system wants to purchase more parts than the expected demand forecast. If the lifetime buy ratio is less than one, the optimum solution for the system is to purchase fewer parts than the expected demand forecast, part obsolescence year, and variable setting.

The lifecycle cost ratio (14) have a similar interpretation as the lifetime buy ratio results. When the lifecycle cost (LCC) ratio is equal to one, the optimum lifecycle cost is equal to the lifecycle cost for purchasing the forecasted expected demand for the same production profile and part obsolescence date. If the lifecycle cost ratio is greater than one, the system is paying more for the lifetime buys than purchasing the forecasted expected demand quantity. If the lifecycle cost ratio is less than one, the

system is paying less than the lifecycle cost for the forecasted expected demand quantity.

DEFAULT LOT Qty	LCC mean ($)	LCC std dev ($)	LTB Qty / Demand Qty	LCC / Demand LCC	LTB Qty / Default LTB Qty	LCC / Default LCC
Demand						
184342	146979.42	35477.34	1.00	1.00	0.9923	1.1804
LTB						
185773	124520.39	2587.58	1.0078	0.8472	1.00	1.00
80% of Demand						
147474	4977008.19	94801.20	0.8000	33.8619	0.7938	39.9694
90% of Demand						
165908	2260971.84	82622.40	0.90	15.3829	0.8931	18.1574
100% of Demand						
184342	149635.02	38696.87	1.00	1.0181	0.9923	1.2017
110% of Demand						
202776	141396.83	225.18	1.10	0.9620	1.0915	1.1355
120% of Demand						
221210	159883.08	232.08	1.20	1.0878	1.1908	1.2840

Table 3. Default setting results for single part case

3.3.3 System Unavailability Penalty

When the decision to make a lifetime or bridge buy is made to sustain the system for the remainder of its planned production or sustainment period, if the purchase quantity runs short the part may or may not be available for production and a second purchase. When a critical part becomes unavailable, it renders the entire system non-producible. Commonly, system unavailability penalty costs are due to broken contractual agreements with customers, loss of profit, and/or loss of customer base. System unavailability cost is allocated for every system made unavailable due to the part unavailability, rather than every unavailable component.

In the single-part case, Figures 11 and 12 show the results of varying the system unavailability penalty for different demand profiles with part obsolescence in 2005.

Figure 11 graphs the lifetime buy ratio versus system unavailability penalty. Figure 12 graphs the lifecycle cost ratio versus the system unavailability penalty.
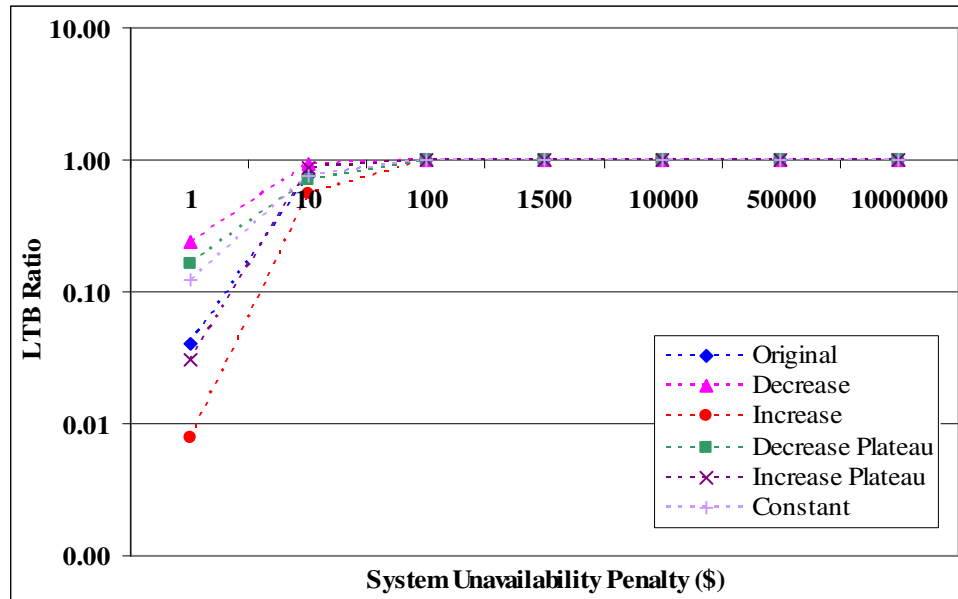

Figure 11. Graph of LTB ratio at the default setting over varying system unavailability penalty for different demand profiles (see Figure 10 for definition of the demand profiles).
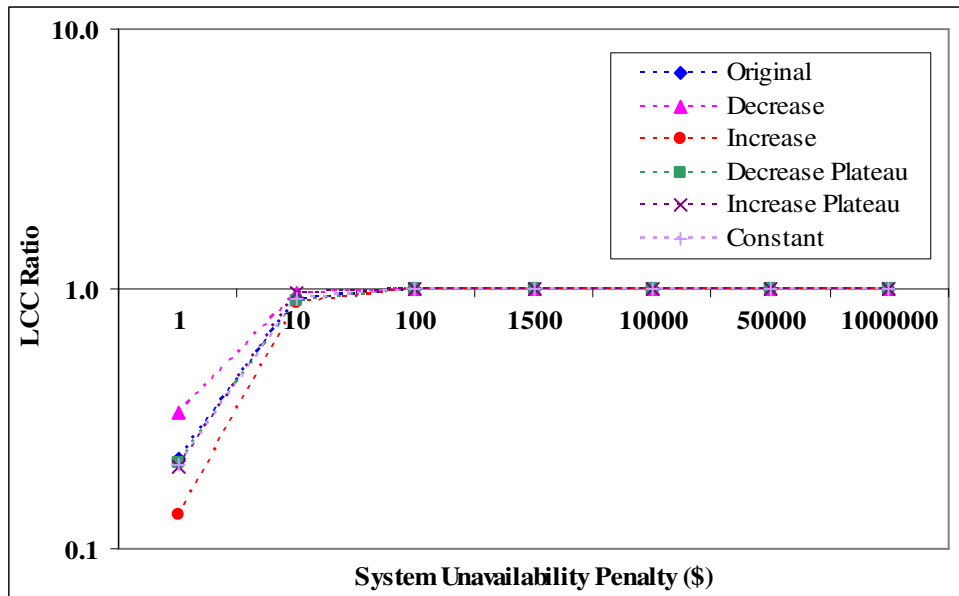

Figure 12. Graph of LCC ratio at the default setting over varying system unavailability penalty for different demand profiles (see Figure 10 for definition of the demand profiles).

For all demand profiles graphed, as system unavailability penalty increases, lifetime buy quantity ratio and lifecycle cost ratio increase to an asymptotic level. To

optimize lifecycle cost, the LOTE software compares the cost of purchase and inventory with the penalty cost. The greater the number of parts in stock, the higher the purchase and inventory costs. With more parts in stock, fewer penalties are incurred for stock shortage. If a lifetime buy was made at or above the expected demand quantity the majority of the sustainment costs would be from procurement and holding. Alternatively, to reduce purchase and holding costs (hence sustainment cost) by purchasing below expected demand quantity will incur shortage penalties (and sustainment cost).

When system unavailability penalty cost is low in comparison to the procurement and inventory costs for the system life, overall it is cheaper for the system to purchase fewer parts than the expected demand solution. Once the penalty increases significantly in comparison to the procurement and holding costs, it is less favorable to pay the penalty and more economical to purchase closer to or above expected demand. Eventually, the lifetime buy quantity reaches an asymptote where there is no need to purchase more than that quantity because the chances of encountering system unavailability are low at the lifetime buy quantity determined. At that point, there will be enough parts in inventory that the system will most likely have sufficient quantities to avoid unavailability and even if it does become unavailable, the costs of the penalty are not high enough to drive the lifetime buy quantities significantly higher.

For systems with an unavailability penalty, the system with the increasing demand profile purchases less lifetime buy part quantities than all other demand profiles. The system with decreasing demand profile purchases the most lifetime buy part

quantities. System unavailability penalty is accumulated each period from the time the system is unavailable to the end of the system lifecycle. The sooner systems become unavailable, the greater the penalty. For increasing demand profile, the majority of the production demand is toward the end of the system lifecycle, while for the decreasing profile product demand is greater toward the beginning of the system lifecycle.

If both increasing and decreasing production profiles purchased the same lifetime buy quantities, the increasing profile would incur penalties later than the decreasing profile as consumption/demand for increasing profile is later in the lifecycle. Therefore, the decreasing profile would have greater penalties than the increasing. To avoid large penalties, the decreasing profile purchase more parts than the increasing profile as shown in Figure 12.

3.3.4 Part Availability Penalty

After making lifetime or bridge buys to mitigate part obsolescence, the quantity of the parts purchased may or may not be enough to last until the system end of life. In situations where the inventory runs short and the part is still available a second purchase from either the original or a third party source is usually accompanied by a cost penalty. The availability penalty is a consequence of resurrecting an out-of-date part, purchasing from a third party source (from which the parts may need to be qualified), or the simple supply and demand system (high demand and low supply yields high prices, low demand and high supply yields low prices).

Figures 13 and 14 graph the lifetime buy ratio and the lifecycle cost ratio respectively versus the part availability penalty. The results are the same for varying availability and unavailability penalties. With increase in availability penalty, lifetime buy ratio and lifecycle cost ratios both increase. For all demand profiles, the lifetime buy ratios are greater than ratios for when the system is unavailable. This is due to the difference in cost allocation. Rather than allocating a single penalty cost for each system that is short from the required inventory (system unavailability penalty), availability penalty is allocated for each part that is short from the required quantity. Availability penalty is allocated much more frequently than system unavailability penalty.
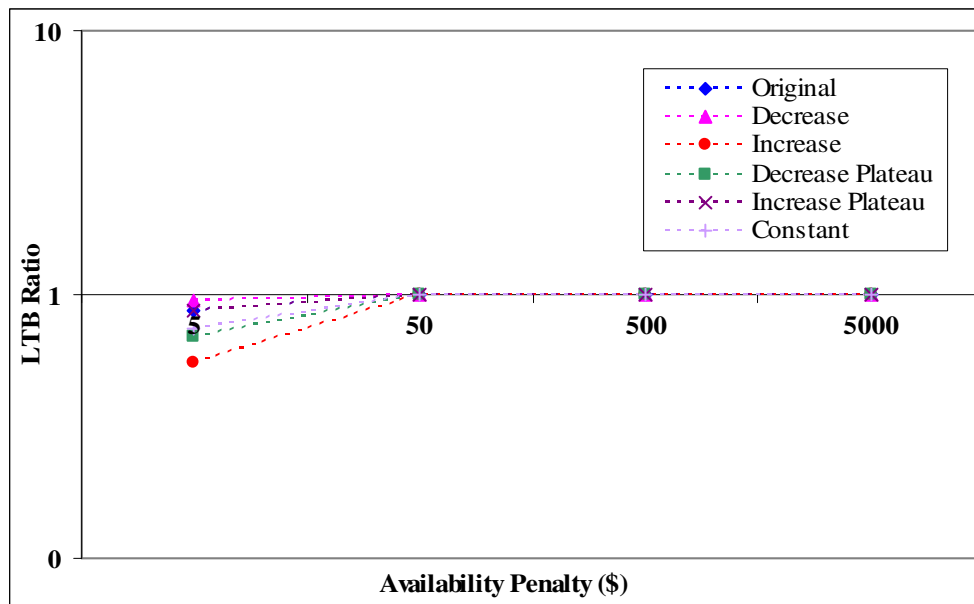
Figure 13. Graph of LTB ratio at the default setting over varying system availability penalty.
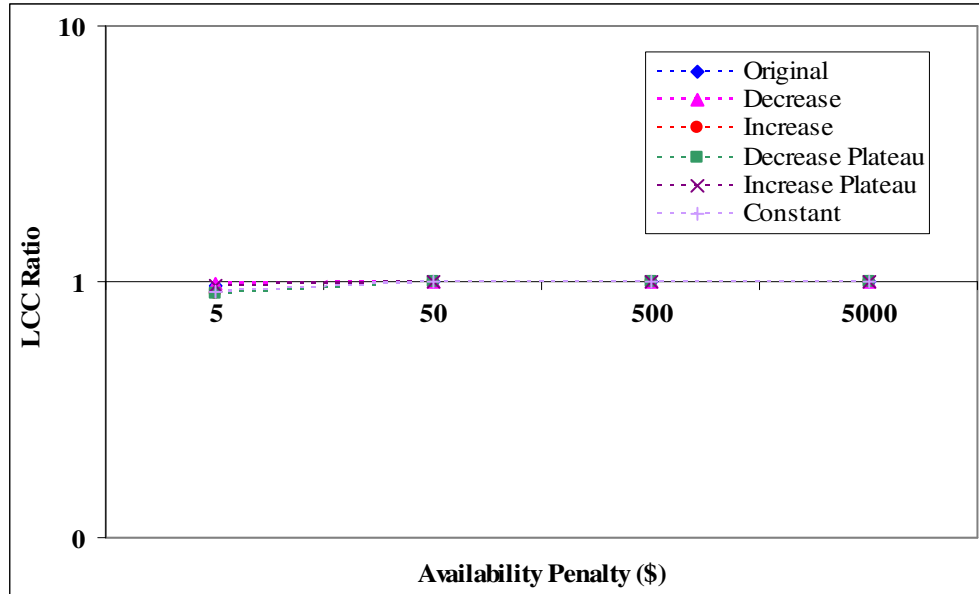
Figure 14. Graph of LCC ratio at the default setting over varying system availability penalty

3.3.5 Holding Cost

Once lifetime or bridge buys are made, the procured parts must be inventoried and maintained for potentially long periods of time. Depending on the part, storage may be as simple as placing them in a secured rented storage site, or as involved as placing them in a temperature, pressure, humidity, dust controlled secured environment [8]. The level of involvement dictates the storage or holding cost. Figures 15 and 16 graph the lifetime buy and the lifecycle cost ratios respectively versus the holding cost.
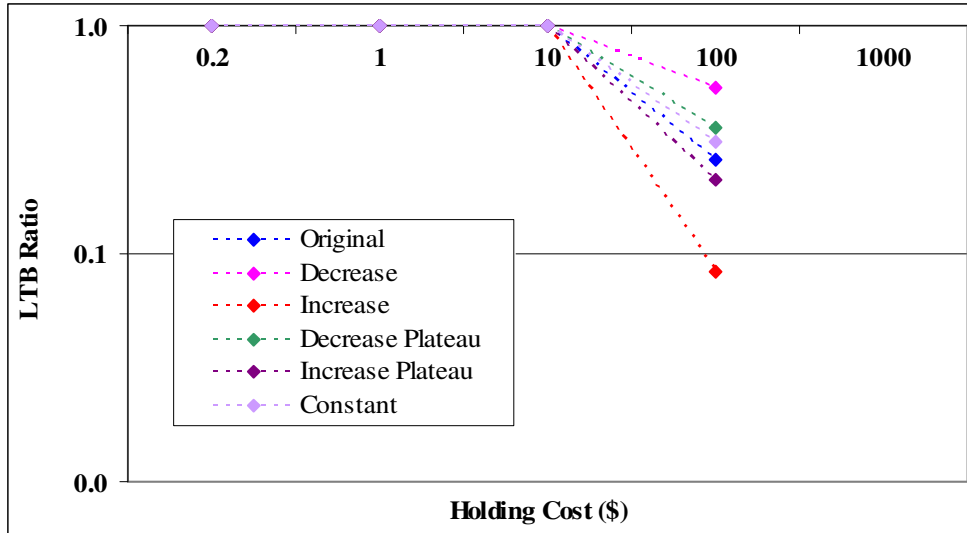
Figure 15. Graph of ratio at the default setting over varying holding cost
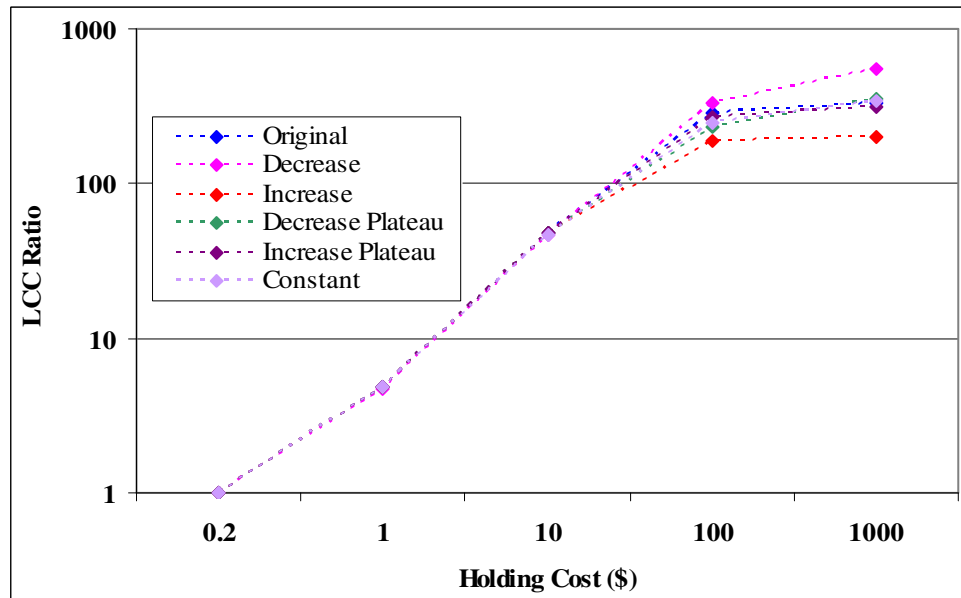
Figure 16. Graph of LCC ratio at the default setting over varying holding cost

The graphs indicate that as holding cost increases, lifetime buy quantity remains very close to expected demand and decreases once the holding cost becomes significant compared to all other cost factors. Initially, holding cost is low compared to unavailability penalty cost in the system. It is more profitable to purchase enough parts to avoid penalties when holding cost is low rather than incurring the penalties.

Incurring more holding cost by purchasing close to the expected demand part quantities is more economical than incurring penalties when holding costs are low. As holding costs increase, holding cost starts to be a large factor in the cost optimization equation. Purchasing significantly less than expected demand decreases the holding cost contribution to the overall lifecycle cost. Although penalties are incurred if parts run out, ultimately it is still cheaper not to pay for high holding costs. Lifecycle cost ratio increases almost directly with holding cost.

As with the penalty costs, the increasing demand profile purchases fewer parts and has less lifecycle cost ratios than the decreasing profile. If both profiles purchase the same quantity of parts, the increasing profile would incur fewer penalties (less sustainment cost) than the decreasing profile (more sustainment cost). Therefore, more parts are purchased by the decreasing profile.

3.3.6 Disposal Cost

At the system support conclusion, if lifetime buys made during the lifecycle were not used, the remaining parts must be disposed of. If parts are disposed of as waste, then disposal cost is considered an increase in the overall lifecycle cost. If the leftover parts are recycled in other systems or resold, the disposal cost is considered a decrease in the overall lifecycle cost. Figures 17 and 18 show the lifetime buy quantity ratio and lifecycle cost ratio respectively versus the disposal cost. The graphs represent situations when parts must be disposed as waste rather than resold.

As disposal cost increases, the system wants to purchase fewer than expected demand quantity to avoid the cost of excess. The lifetime buy quantity graph reaches

55

an asymptote eventually as with other penalties. Eventually regardless of the disposal cost, the lifetime buy quantity is low enough the chances of incurring disposal cost are insignificant. As with holding cost though, with increased disposal cost the lifecycle cost increases significantly.
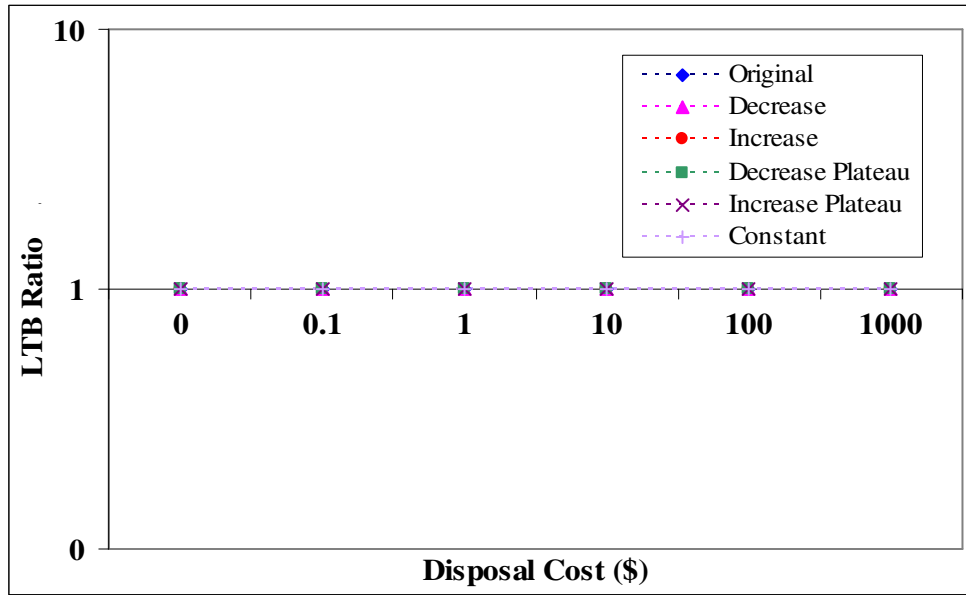

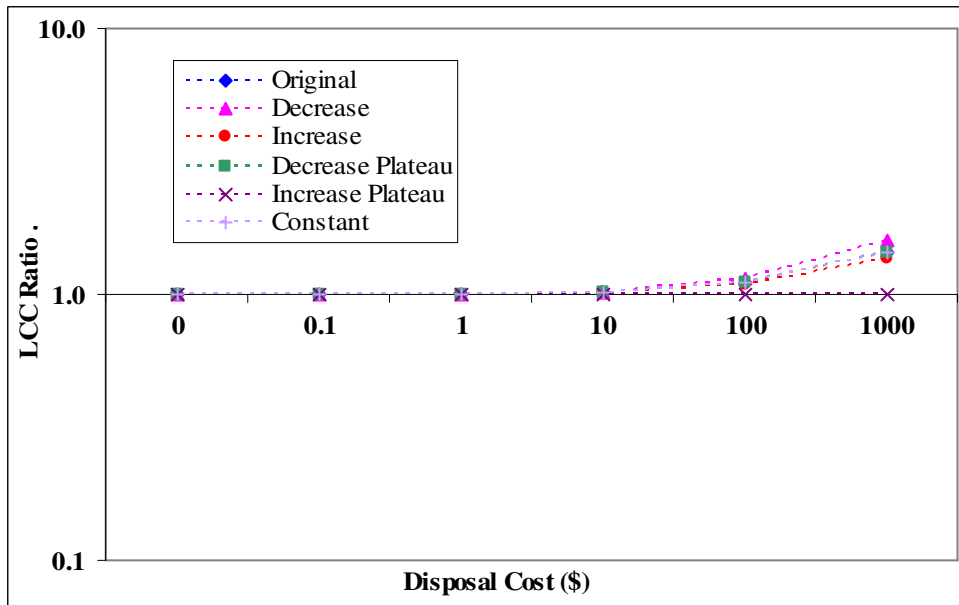**Figure 17. Graph of LTB ratio at the default setting over varying disposal cost**

Figure 18. Graph of LCC ratio at the default setting over varying disposal cost

Unlike demand profile trends for other variables, with varied disposal cost the increasing demand profile purchases more parts than the decreasing production profile. By the same argument used for other variables, if both increasing and decreasing profiles purchase the same quantity of parts, the decreasing profile will consume parts earlier than the increasing profile. To avoid disposal penalties, the decreasing profile can purchase fewer parts than the increasing profile to reduce lifecycle cost. Still, for all demand profiles and at all disposal costs, lifetime buys are all very close to one.

3.3.7 Obsolescence Date

Another major factor affecting lifecycle cost and lifetime buy quantity is the part obsolescence date. As obsolescence date shifts, production profiles shift their lifetime buy and lifecycle cost ratios with changing expected demand quantities. To model the result shift due to obsolescence date changes, Figures 19, 20, 21 show the lifetime buy ratio versus system unavailability penalty with the obsolescence date for the part at 2005, 2012, and 2020 respectively. These dates correspond to the start, middle, and end of the product manufacturing period.
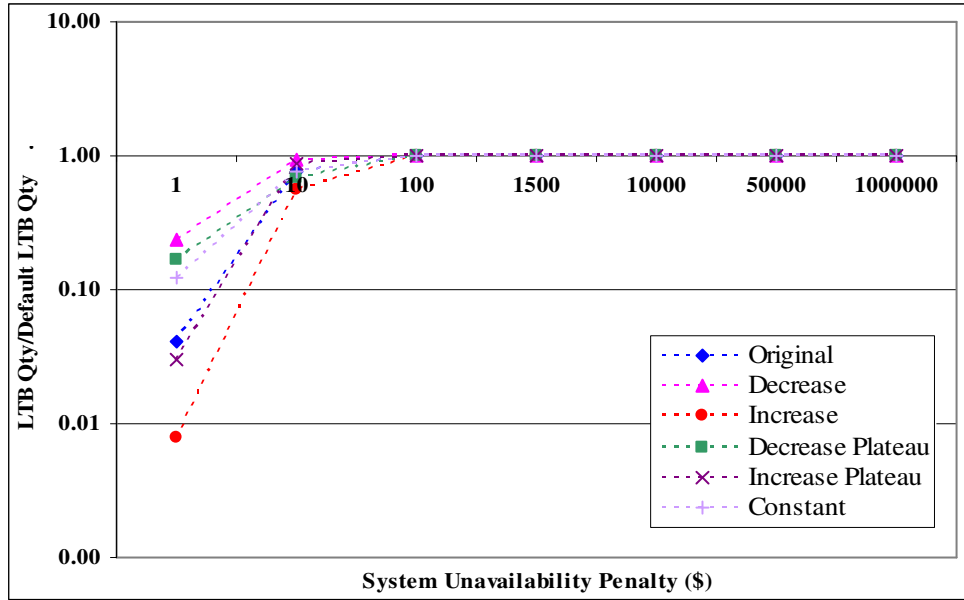
Figure 19. Graph of LTB ratio at the default setting over varying system unavailability penalty. Obsolescence year is 2005.
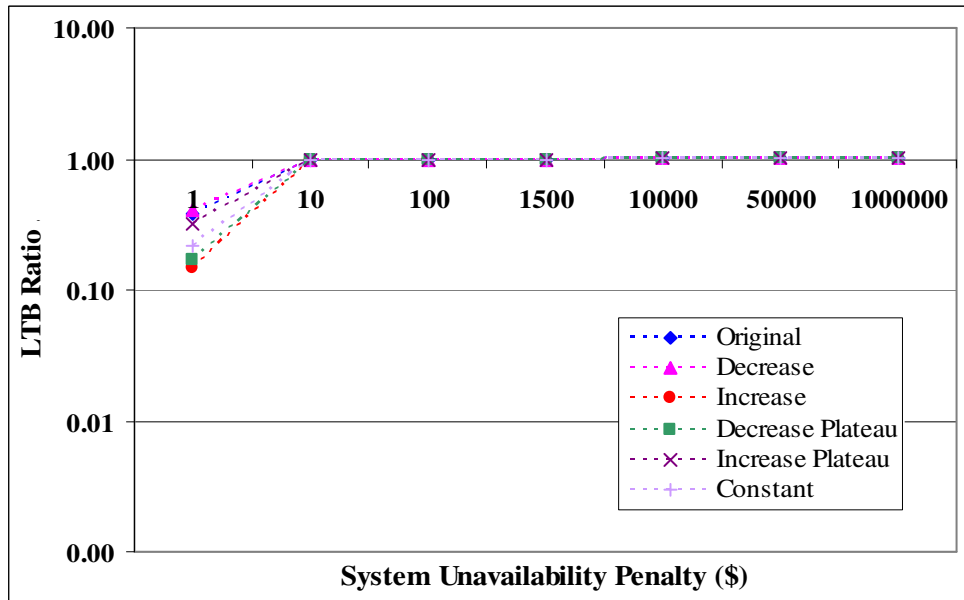

Figure 20. Graph of LTB ratio at the default setting over varying system unavailability penalty. Obsolescence year is 2012.
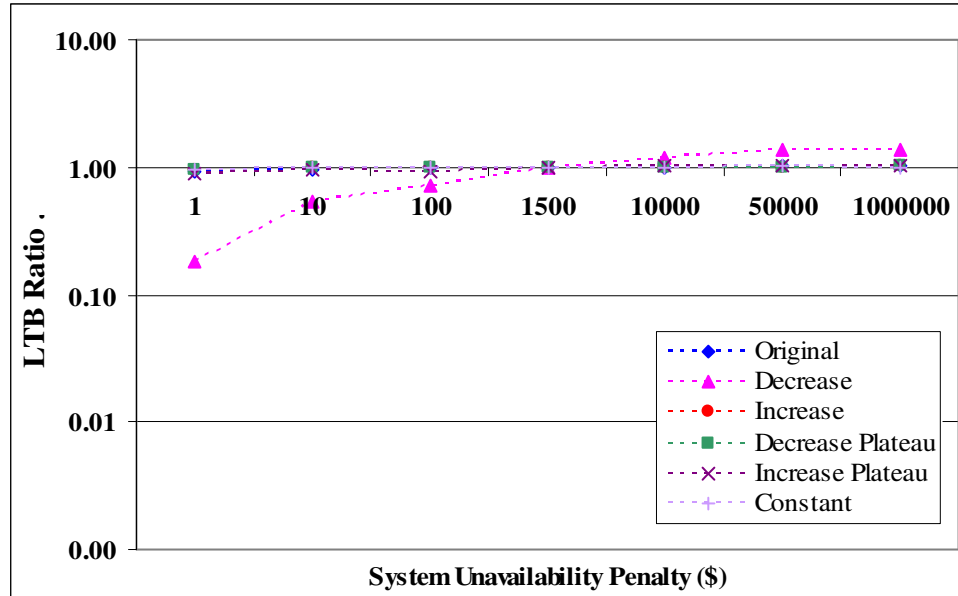
Figure 21. Graph of LTB ratio at the default setting over varying system unavailability penalty. Obsolescence year is 2020.

Figures 19-21 indicate as obsolescence date increases the lifetime buy ratio for all production profiles with the exception of the decreasing profiles shift higher. When the obsolescence date is set to 2012 (product lifecycle mid-point) all non-decreasing profiles increase in lifetime buy quantity closer to the expected demand lifetime buy quantity compared to an obsolescence date set to 2005. As the obsolescence date shifted from 2005 to 2012, the total demand for the decreasing profiles became significantly less than total demand for non-decreasing profiles. If all profiles purchase the same quantity, the increasing profiles will incur penalties earlier than the decreasing profile. To avoid penalty the non-decreasing profiles purchase closer to expected demand lifetime buy quantity.

When obsolescence date is set to 2020, the decreasing profile decreases in lifetime buy ratio while other profiles increase closer to one. By 2020, the decreasing profile has significantly lower total expected demand than all other profiles. Graphs

of system availability penalty, holding cost, and disposal costs at the three varying obsolescence dates (2005, 2012, 2020) are shown in Appendix B.

3.3.8 Motorola Single-Part Case Study Summary

The lifetime buy problem is complex and controlled by a number of part related variables. The single-part case results in this section have shown that changes in any of the variables (system unavailability penalty, part availability penalty, holding cost, disposal cost, procurement cost, and part obsolescence date) can have a significant affect on the lifetime buy quantity and the lifecycle cost. Additionally, system related variables such as demand and supply profiles also contribute to the problem's complexity. This example demonstrates a relatively intuitive finding for managing a single part, in the next section, all the parts in the Infrastructure Base Station will be considered concurrently to account for equal run-out.

3.5 Motorola Infrastructure Base Station Full Study

The components and production data from the infrastructure base station were used in the MOCA (Mitigation of Obsolescence Cost Analysis) tool to determine an optimum refresh plan using the.[8] The data from the MOCA analysis was used as input for LOTE analysis to find the optimum lifetime buy quantities. Based on conversation with Motorola [13], the following default data was specified:

- Non-recurring Cost: $200,000 per part (available after obsolescence, but requires resurrection fee)
- Availability Penalty: 3x Unit Cost/Part

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[8] The refresh planning study is not part of this thesis.

- Unavailability Penalty: $2,000/System
- Holding Rate: 5% Unit Cost/Part
- Cost of Money (discount rate): 10%
- Net Present Value Baseline Date: 2005
- Demand Distribution: Poisson Distribution
- Refresh Date: 2011

Based on these specifications, sensitivity analyses were conducted for holding cost, availability penalty, unavailability penalty, and refresh date existence.

3.5.1 Motorola Holding Cost

Motorola specified that inventory costs for the Infrastructure Base Station should be approximately 5% of a part's unit cost. Given this information, the holding cost was varied at 1%, 5% and 10% to monitor the effect of holding cost on overall lifecycle cost. To compare lifecycle cost results at varied holding costs, the lifecycle cost ratio was used as a comparison tool.

Lifecycle Cost Ratio			
(Lifecycle Cost using Monte Carlo Analysis / Lifecycle Cost at Demand)			
Penalty Multiple of Unit Cost / Part	1 %	5 %	10 %
1 x	0.654136	0.580773	0.509839
2 x	0.963261	0.917052	0.853734
3 x	0.998435	0.987293	0.959372

Table 4. Affect of availability penalty variation and holding cost variation on lifecycle cost ratio (no refresh).

Lifecycle Cost Ratio			
(Lifecycle Cost using Monte Carlo Analysis / Lifecycle Cost at Demand)			
Penalty Cost / System	1 %	5 %	10 %
$ 1,000	0.668627	0.627993	0.58832
$ 2,000	1.10522	0.931636	0.855091
$ 3,000	1.351625	1.234528	1.121245

Table 5. Affect of unavailability penalty variation and holding cost variation on lifecycle cost ratio (no refresh).

Tables 4 and 5 give the lifecycle cost ratio results for a system with the Motorola specified settings, no refresh dates, and variations in the availability penalty, unavailability penalty, and holding costs. Take notice of the lifecycle cost ratios for each penalty setting at varying holding percentages. A ten fold increase in holding percentage has a very small affect on the over lifecycle cost ratio. For example, at availability multiplier of 3 times part unit cost, the difference in lifecycle cost ratio between 1% and 10% holding costs is less than 3%. This shows that variation in holding cost for the Motorola Infrastructure Base Station product is insignificant. The focus should be on penalty sizes and their effects on lifecycle cost ratios and lifetime buy ratios.

3.5.2 Motorola Lifetime Buy Results

Based on the information provided by Motorola, Figure 21 shows the lifetime buy ratio for all parts purchased versus their purchase dates. The figure takes into account a refresh date in 2011, as determined through MOCA. Since holding cost was determined from the previous section to have a small affect, it was set at the Motorola specified 5% of unit cost per part. Figure 22 plots results for a variety of availability penalty scenarios. The first few results are for zero non-recurring costs and varied availability penalty multipliers of 1, 2, 3, and 300 times the unit cost per part. The results for availability penalty equal to unit cost are very close to zero and are not visible in this figure. The penalty is so small that the system would rather run short of inventory after lifetime buy and pay for penalties than purchase more parts. The system is purchasing much below expected demand. As availability penalty increases

to 2 and 3 times the part unit cost, the lifetime buy ratio for each part jumps to very close to, but below one for most cases. In these situations, the penalty cost becomes a significant factor in the lifecycle cost equation and pushes the lifetime buy quantity close to but still below expected demand to avoid penalties.

Three other cases graphed in Figure 22 have an additional non-recurring cost with the availability penalty of 3 times part unit cost. Motorola stated that it is common when inventory becomes short for product suppliers to request for part resurrections from manufacturers. Part resurrection refers to requests that manufacturers receive to restart manufacture of an obsolete part. The cost estimate from Motorola for a non-recurring resurrection is $200,000 per part. Figure 22 graphs 3 cases where non-recurring costs are set at $100,000, $200,000, and $300,000 in addition to an availability penalty of 3 times part unit cost for each part. For all three cases, the penalties are so high that the system purchases more than expected demand for all parts to avoid incurring penalties. In fact, these results are very similar to results for zero non-recurring cost but high availability penalty of 300 times the part unit cost. Regardless of how penalties are allocated, once they become very high in comparison to all other costs in the system, the system behaves very similarly for all cases. LOTE purchases greater than expected demand consistently for all parts. It purchases just enough parts that penalties are very unlikely to occur and not many more parts above that quantity. Figure 22 shows that all lifetime buy ratios hover between 1.01 and 1.07. These systems purchase between 1% and 7% more than expected demand overall.

There are a small number of parts that have lifetime buy ratios much greater than other parts at the same analysis. It was found that these parts have very low unit costs; many actually have a unit price of zero. Purchasing significantly above the expected demand quantity for these zero unit cost parts has no negative affect on the lifecycle cost ratio, especially since inventory cost has been set to 5% of unit cost ($0). Therefore it is beneficial to over-estimate their lifetime buy quantities greatly.
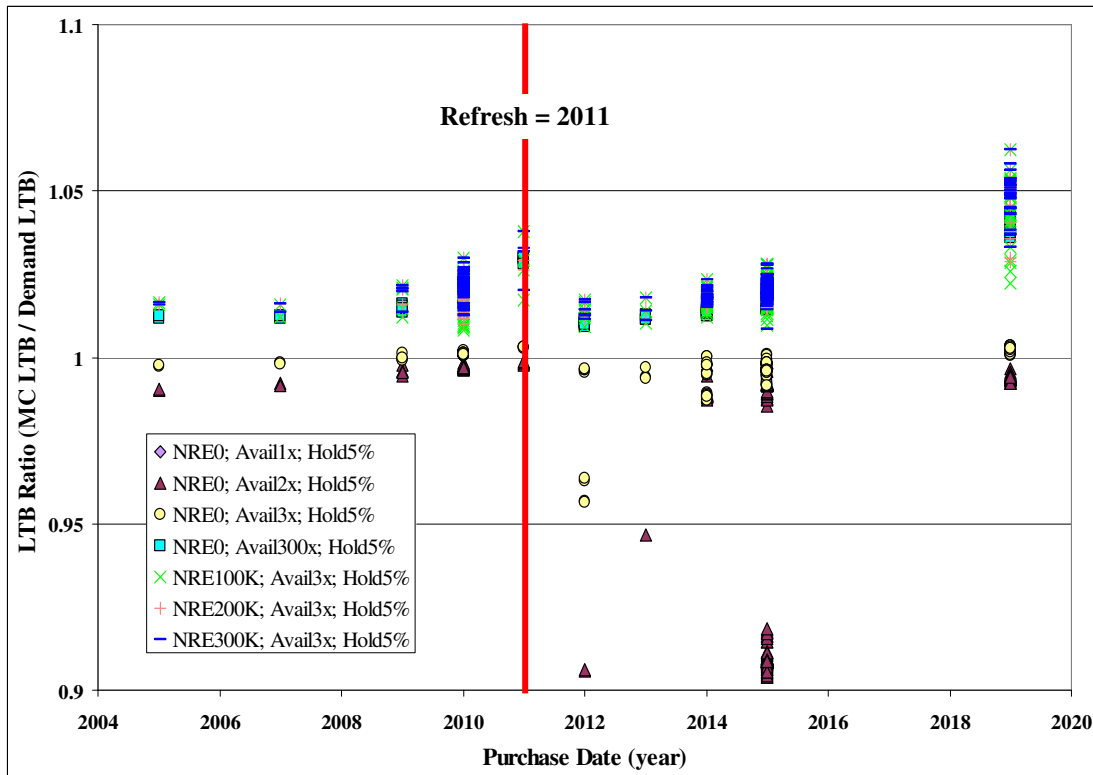

Figure 22. Lifetime buy ratio for variations in availability penalty (refresh = 2011, holding rate = 5% unit cost/part)

Figure 23 graphs the same data as Figure 22, but without the refresh date. In Figure 23, the vertical spread in data is much greater than with the refresh date in 2011. The pattern of increased lifetime buy ratio with penalty is the same as with a refresh date. There is an upward trend in the no refresh data for lower penalties. As purchase date increases, the lifetime buy ratio also increases. This is shown more prominently in Figure 23.The further away from the end of support date, the lower the

lifetime buy ratio. This demonstrates that LOTE is balancing between the cost of money, procurement cost, inventory cost, and penalty cost.
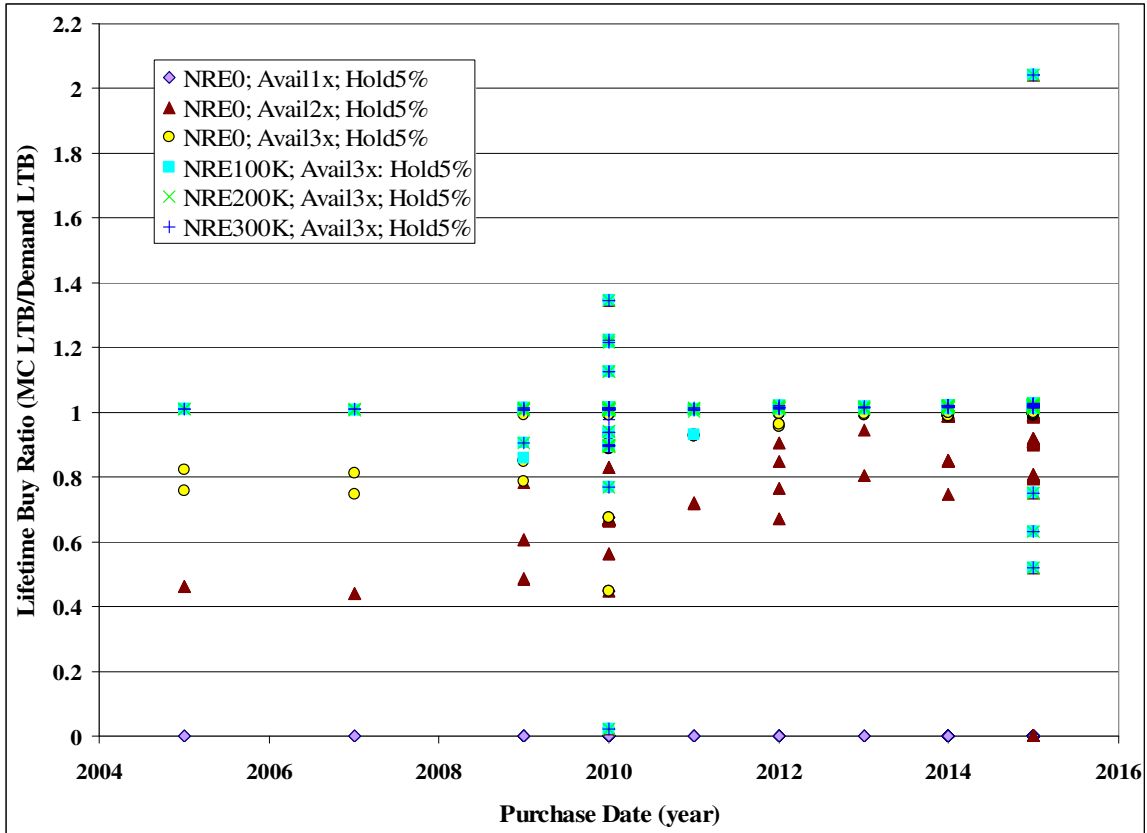
Figure 23. Lifetime buy ratio for variations in availability penalty (no refresh, holding rate = 5% unit cost/part)

To demonstrate that the optimum solution does provide the solution with the lowest lifecycle cost, Figure 24 shows the lifecycle cost ratios for purchasing at various percentages of the expected demand quantities. Figure 24 shows the lifecycle ratios for LTB quantities ranging from 10% of expected demand to 120% of expected demand at the Motorola provided specifications with 1 refresh in 2011. The optimum solution is the minimum point graphed on Figure 24. The demand percentage it is graphed at is the average of the LTB ratios for all purchased parts, approximately 102%. This point on the graph corresponds to results from Figure 22 with non-

recurring cost at \$200,000, availability penalty at 3 times part unit cost, and holding cost at 5% of part unit cost.
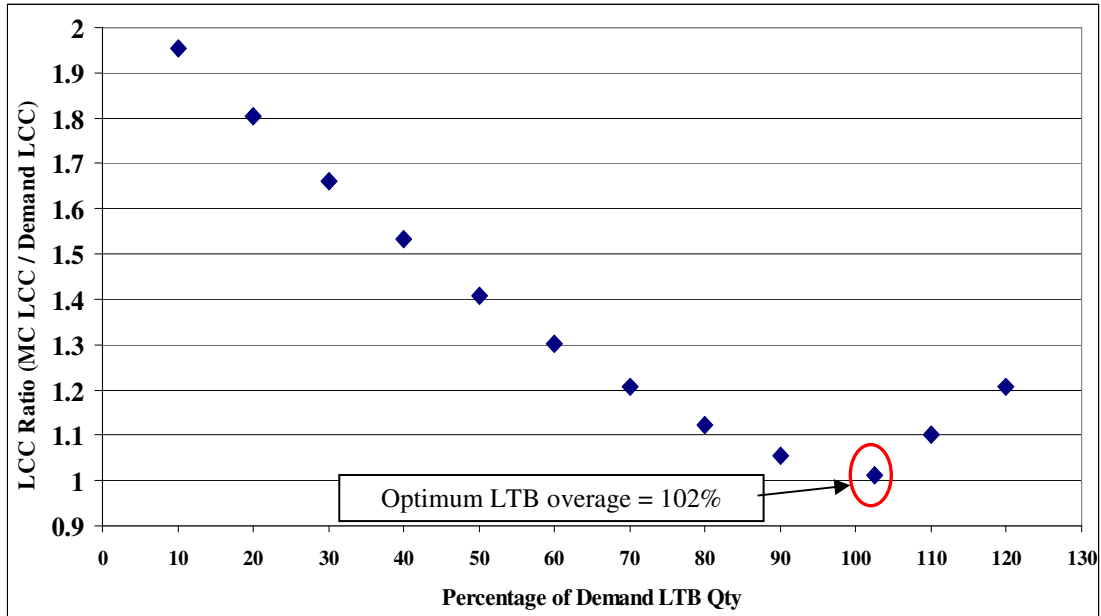
Figure 24. Lifecycle Cost Ratio versus Percentage of Demand Qty (1 refresh = 2011)

3.5.3 Historical Motorola Lifetime Buy Buffers

Motorola has been collecting lifetime buy quantity information since the late 1990s. Based on information they are provided from their business and engineering departments about product demands, persons at Motorola who make lifetime buys often add a buffer size to the demand prediction. The buffer is a percentage of parts to purchase above the demand prediction provided. It is the equivalent of the lifetime buy ratio in percentage format. It is roughly estimated based on a number of variables such as product size, lifetime, and technological complexity.

Tracing back to Motorola's historic lifetime buy and bridge buy data, Figure 25 shows all the lifetime buys and bridge buys that Motorola has recorded for all systems that require lifetime buys and/or bridge buys (not exclusive to the Infrastructure Base

Station). The data is divided into 3 sets, lifetime buys, bridge buys, and any buys made without a buffer (at demand) before 2004. In 2004, the buffer was formally introduced by an employee (Sam Booras) at Motorola. Prior to this date although some buffers may have been added to demand predictions, there was no formal process to insert a buffer based on the part specifications.

For lifetime buys, the average buffer size Motorola uses is approximately 39% (lifetime buy ratio = 1.39). Bridge buys have average buffer sizes of about 23%. These are significantly larger than the LOTE recommended lifetime buy ratios of 7% at most. There were a significant number of parts purchased without a buffer before 2004. As previously mentioned, buffers were not introduced until that time frame. Thus, as expected, the majority of zero buffer purchases were made before that time. For both lifetime buys and bridge buys, there are also purchases made without buffers added.
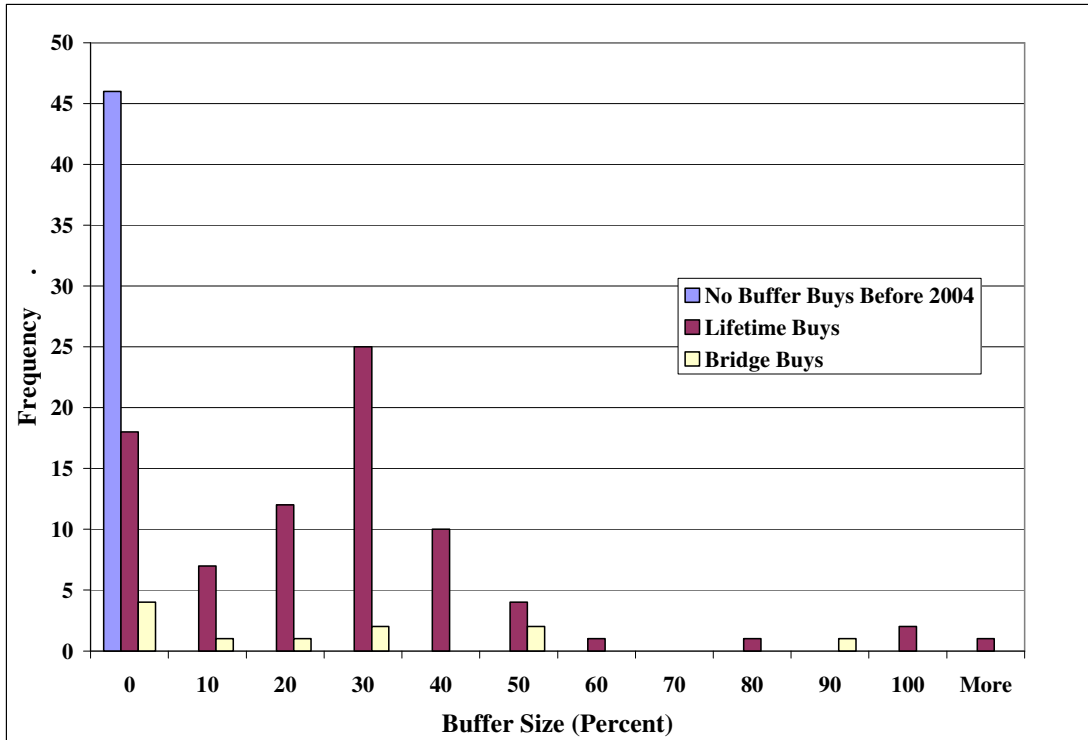
Figure 25. Historic Motorola lifetime buy buffer sizes.

LOTE's analysis of the infrastructure base station indicates maximum lifetime buys of approximately 7% over expected demand. Figure 25 indicates that Motorola is over purchasing on its lifetime buys. There are a number of explanations for the discrepancy between the LOTE results and the Motorola historic data. When making lifetime buy decisions, Motorola does not consider the cost of inventory and cost of money. They mainly emphasize avoiding part shortages. Engineers feel the short-term pain associated with running short of parts and overcompensate by buying too many parts at lifetime buys without a view to the actual lifecycle costs. Equal attention is not placed on all costs that contribute to lifecycle cost. If this is the case, Motorola should start taking notice of all their cost factors, not just the penalties. If this is the case, the results show that any company that makes lifetime buys to sustain

68

its business should pay closer attention to all lifecycle costs (especially the inventory costs and cost of money) rather than just focusing on the penalties.

Another explanation may lie with the input data to the model. The Monte Carlo analysis used in LOTE distributes uncertain values based on a user specified distribution model. All results generated from LOTE have used a Poisson distribution for the expected demand. This distribution is commonly used to generate stochastic values for expected demand predictions at companies such as Motorola. Searching through the LOTE output, the Poisson distribution variation percentage from the input mean is on average 4% less than or greater than the given mean. This is 1 to 2 standard deviations away from the mean.
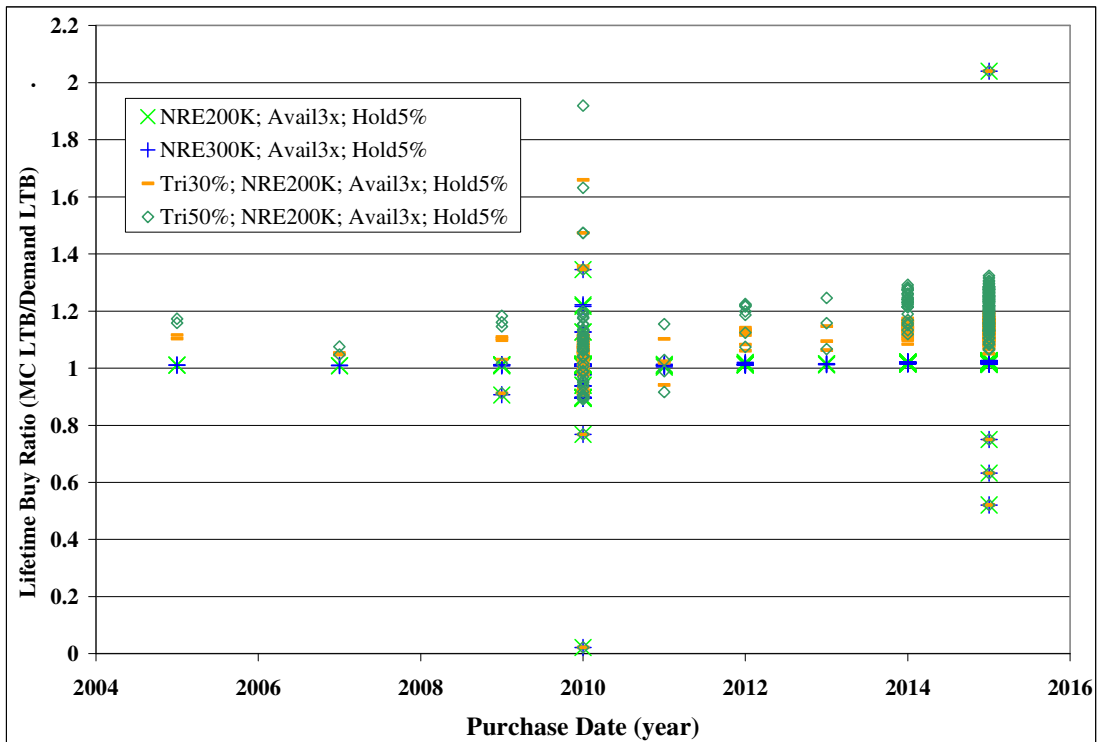
Figure 26. Triangular distribution results of lifecycle cost ratio versus purchase date (no refresh)

Figure 26 plots the results for a triangular distribution with 30% variation and 50% variation on either side of the mean demand values provided in the production

69

data. The triangular distribution feature in LOTE allows users to specify the amount of variation from the given mean to the left and right of the mean. At 30% variation for the triangular distribution, the lower limit of the distribution is 30% less than the mean, and the upper limit of the distribution is 30% greater than the mean. The same goes for 50% variation for a triangular distribution. For example, with a triangular distribution of 50%, the distribution is assuming that demand could be off by 50% either less than or greater than the given demand value. This allows for greater uncertainties in the lifecycle cost calculations than the Poisson distribution, which only had about 4% variation on either side of the demand mean. As speculated, the triangular distribution with 30% variation has higher lifetime buy purchases than the Poisson distributions with approximately 4% variation. However, even at 30% variation (recommended by Motorola) the lifetime buy purchases are still only 5% - 10% above the expected demand quantities. At a drastic 50% variation from the mean demand, the triangular distribution makes lifetime buys that are 10% to 20% greater than the expected demand quantities.

These results indicate that even if the LOTE implemented Poisson distribution is a tighter distribution than used by Motorola, the lifetime buy buffer sizes from the Triangular distribution at 30% are still lower than those used at Motorola currently. Currently Motorola uses on average a 39% buffer above their forecasted demand values to make lifetime buys. LOTE would suggest between 5% to 10% buffer sizes.

3.6 Summary

This chapter demonstrated the logic used by the Life of Type Evaluation (LOTE) tool on simple cases. It has also shown LOTE's capability to analyze complex, multi-part systems with refresh dates, changing demand profiles, and modified demand distributions. The results for the Motorola Infrastructure Base Station case indicate that demand distribution plays an important role in the results obtained. The LOTE results have also revealed that Motorola may be placing more emphasis on their penalties and less on the inventory and procurement costs that are equally important in solving for lifecycle cost, and as a result may be consistently overbuying their lifetime buys.

Chapter 4 Summary, Conclusions and Future Work

4.1 Summary

The work done in this research effort focuses on DMSMS obsolescence and the lifetime buy problem for electronic parts. The goal is to create a practical model that includes factors affecting DMSMS obsolescence and lifecycle cost, and use this model to minimize lifecycle cost through lifetime buy quantity optimization. The work in this thesis is organized into three parts, model extension, evaluation and validation of the model, and application of the model to a real problem. The model used in this research is based mainly from the work of Fortuin and Teunter [25]. The Fortuin and Teunter model was extended into a practical software application (called LOTE) that can analyze a multi-part system with refreshes, varying demand profiles, and uncertainties in costs.

To validate the model, a number of examples were provided that range from simple calculations for a single part analysis to complex multi-part systems. These examples allow an understanding of the contributing variables to the lifetime buy problem– procurement cost, inventory cost, penalties, obsolescence dates, demand profiles.

The Motorola Infrastructure Base Station was analyzed using specifications provided by Motorola. Sensitivity analyses were conducted on the data for cases with and without refresh dates. The overall results showed that when the penalties for running out of parts are high, LOTE recommends purchasing above the expected demand values. However, by balancing the inventory and procurement costs with the

penalty costs, results indicate that Motorola is using higher buffer sizes than LOTE recommend. LOTE indicates that organizations often give inventory shortage penalties a greater emphasis than inventory and other hidden costs (such as the cost of money) because of the negative attention that penalties attract and the short term "pain" that they inflict.

4.2 Contributions

Although the work presented in this thesis is based on the work of Teunter and Fortuin, it takes their research much further. The Life of Type Evaluation (LOTE) tool is a practical application that is user friendly and available as stand-alone software. LOTE mimics real lifetime buy and bridge buy situations that many companies such as Motorola face. The results section demonstrated that LOTE is capable of simulating a real lifetime buy case faced in the commercial sector. Specific contributions made by this thesis are:

- The final order treatment of Fortuin and Teunter was extended and generalized to include multi-part analysis (Teunter and Fortuin solve the problem for one part at a time), refreshes, varying demand profiles with a number of stochastic distribution options, and a practical search algorithm for efficient solution generation.

- The work in this thesis represents the first application of an optimization process to the DMSMS electronic part lifetime buy problem.

- The results of the Motorola case suggest that many organizations are likely overbuying when making lifetime buys or bridge buys of electronic parts.

Currently, a greater emphasis is placed on inventory shortage penalties than other cost factors that contribute to overall product lifecycle cost. The results indicate that companies need to evaluate how lifetime buys and bridge buys are made within their organizations. They need to account for all contributing factors before making a final decision on the quantity of parts to purchase at lifetime buy or bridge buy.

This research links theoretical models on lifetime buys with real industry data and practices to create a more accurate model on lifetime buys and bridge buys. Working with Motorola has developed a more robust and accurate model of lifetime buys that mimics how these decisions are made in industry. Likewise, the model has provided insight for Motorola on their lifetime buy purchasing process and how it can be improved.

4.3 Future Work

In the original extended version of the Fortuin and Teunter model, the plan was to distribute the obsolescence dates along with demand costs and penalties in the stochastic analysis. However, there are many factors that require further consideration if this feature is added. With changing part obsolescence dates, lifetime buys calculations for each sample must account for the new obsolescence date order. The final results must also be able to demonstrate that the obsolescence dates have been distributed. Much more thought is required for this implementation if it is made.

In order to model real data accurately, more research needs to be conducted on buffer sizes and the actual consumptions from real industry lifetime buys. This will

give insight into the type of uncertainty distribution that LOTE should be using and the size of the data variation. This can be done by following up with the historic lifetime buy buffer size data from Motorola and monitoring the actual consumptions of those lifetime buys. It was briefly mentioned in a previous chapter at the end of a product lifetime, the product support (and/or manufacturing) may be re-evaluated and extended for a longer period. Unanticipated life extensions are a common problem that complicates lifetime buys for military and other types of systems. Further research should be conducted on the frequency of product life extensions.

APPENDICES

Appendix A – Life of Type Evaluation (LOTE) Tool User's Guide - Abridged

This appendix contains an abridged version of the LOTE User's Guide. See Reference 9 for the complete user's guide.

LOTE Windows

The LOTE tool is written in Java code. It is a stand along application that can be downloaded through the Center for Advance Life Cycle Engineering (CALCE) website (http://www.calce.umd.edu) by all CALCE consortium members. Figure 27 shows the start up window, with the boxed region indicating the user options: File, Inputs, Run, Results, and Help.
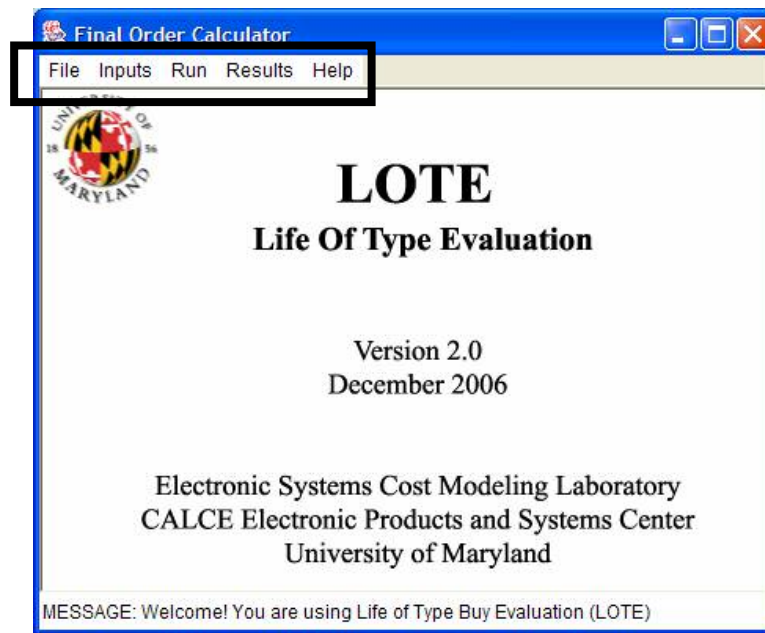
Figure 27. LOTE start up window and user options.

The File pull down menu in the LOTE application allows users to input data for analysis, load and save results, reset all data back to default, and change the operating mode. LOTE has two operating modes, Default and Development. The Default mode is for the common user. It has all the basic functions to enter data, change settings, and run different analyses. The Development mode is an experimental form that allows application developers to work with new features and improve the application.

To run any analysis, LOTE requires component data and production data at the least. This information can be loaded through the File menu (Read Input Component File, Read Input Production File, Load System) shown in Figure 28. Component and production files inputted separately must be in comma delimited format (.csv). Comma delimited form is an option on spreadsheet applications.
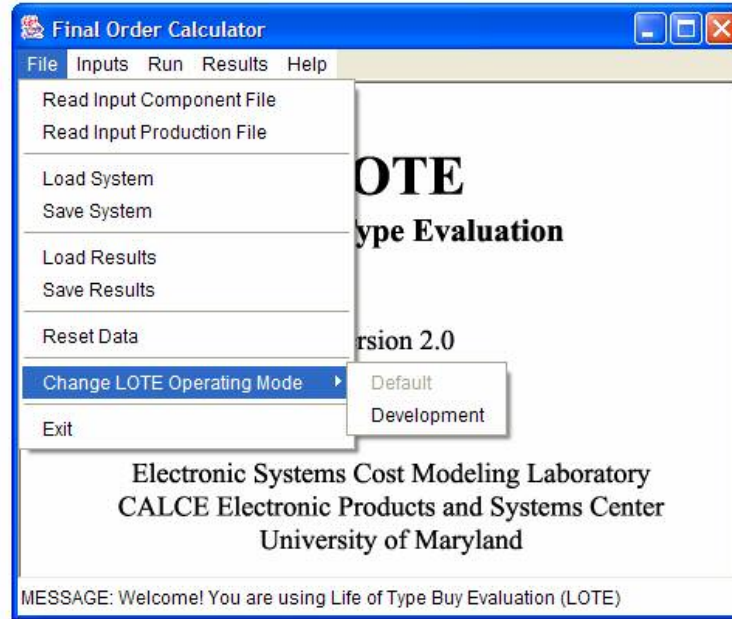
Figure 28. File pull-down menu.

Component and production data can also be manually entered through the options under the Inputs pull-down window shown in Figure 29, along with other analysis related data and settings. The Design Refresh Data option allows users to insert design refresh dates. Users can change system settings in the Solution Control Data window. To modify the analysis type (Monte Carlo On/Off), users must go to the Analysis Options window. Lastly, the Part Synthesis Data has lifetime information about the various types of parts listed in the Components Dialog.
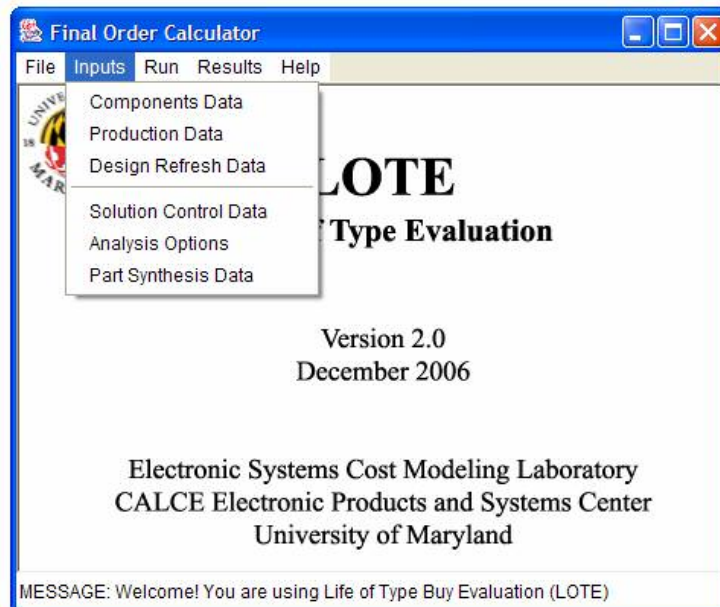
Figure 29. Input pull-down menu.

78

In the component data window, the input required are: part name, part cost/unit, quantity/system, obsolescence date, part type, initial quantity, holding rate/unit, penalty type, penalty cost/unit, and disposal cost/unit. The user can also choose the part in the system to include in the analysis using the + and – column to the left of the part name column. Figure 30, gives an example Component Data window with input data.

Figure 30. Component Data window.

To run any analyses, LOTE also requires production information in addition to components data. Figure 31 shows an example Production Dialog Window with data. Users can also change the Monte Carlo distribution for the production demands and supplies. Users are given the option of None, Normal, Poisson, and Triangular distributions. However, the distribution is only used if the Monte Carlo option is turned on in the Analysis Options Window.

Figure 31. Production Dialog window.

In situations when the system has a known refresh, users must enter refresh dates in the Design Refresh Options window in Figure 32. There is also the option to enter look-ahead times. Look-ahead times are specified number of years ahead of the refresh date(s) indicated within which the refresh designer will look for parts that will be going obsolete. Any parts that become obsolete during the design refresh or within the look-ahead period specified will be redesigned. Since redesigns are generally very costly, it is common to insert look-ahead times and capture obsolete parts within years to the future of the redesign in order to get the most benefit out of the redesign.
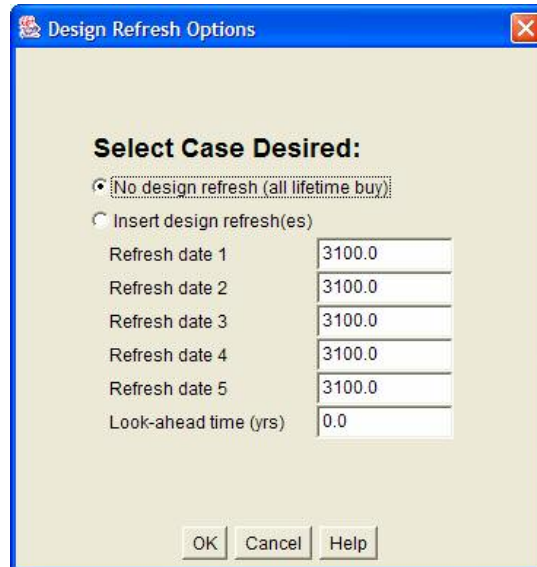
Figure 32. Design Refresh Options window.

Other analysis data can be controlled in the Solution Control Window, Figure 33. Depending on the industry this technology is used, the Discount Rate in percent/year can be changed to reflect industry standards. The default value is set at 10 percent/year. The base year that the discount rate is calculated to is set in the Discount Rate Base Year. These two settings determine the net present value of money at the discount rate base year. When components are set to unavailable after obsolescence in the Component Dialog Window, the overall system unavailability penalty is set in the Solution Control Window. Additionally, when the user would like to calculate lifetime buy quantity at a percentage of demand and the associated lifecycle cost, she can set the percentage value in Simple Policy. Then to actually make the calculations, she must choose the Demand option in the Run pull-down menu. The Smallest M[9] and Largest M settings refer to the outer ranges for the LOTE search algorithm. The default values are 0 and 1,000,000 respectively to account for most solutions. In cases where the lifetime buy quantity is outside of that range (greater than 1,000,000), the user can enlarge the boundaries. Or, if the user knows that the solution set is within a much smaller range, she can reduce processing time by reducing increasing the Smallest M and/or decreasing the Largest M.

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[9] Smallest M cannot be less than zero. The lowest lifetime buy quantity is zero. Users cannot owe parts.
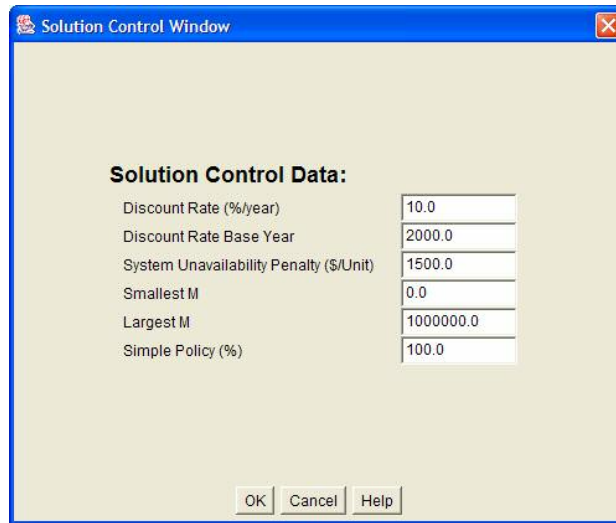
Figure 33. Solution Control Window.

The Analysis Option Window in Figure 34 allows users to control analysis options, mainly to turn the Monte Carlo Analysis On/Off. When the Monte Carlo Analysis is Off, all analysis results are found without distributing any input values (demand, supply, penalty). When the Monte Carlo Analysis is On, users can define the type of values she wishes to distribute, for example cost or quantity and dates. Currently obsolescence dates are not distributed in the LOTE application. However, when the Monte Carlo Cost/Qty option is turned On, the demand, supply, and penalty values are distributed. The distributions for demand and supply are set in the Production Dialog Window. The Symmetric Triangular Distribution on Cost and Date are another type of distribution that can be modeled in LOTE. The number of samples for the Monte Carlo distribution is set at Number of Samples. There is a directly correlation between number of samples and processing time.
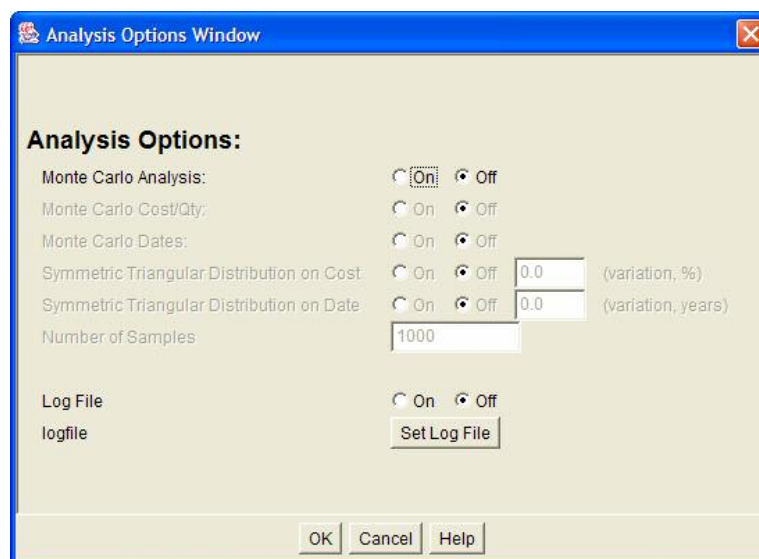
Figure 34. Analysis Options Window.

When design refreshes are inserted, one or more parts are replaced. The replacement parts must be synthesized for the analysis to continue. The part type listed in the Component Dialog Window is linked to the lifetimes listed in the Part Synthesis Dialog (Figure 35) and used to generate new obsolescence dates for synthesized parts. The Lifecode for Synthesized Parts indicates the obsolescence index used for the new part. The lifetimes for each type of part can be changed, and new part types can be entered if a system has parts unlisted in this dialog.
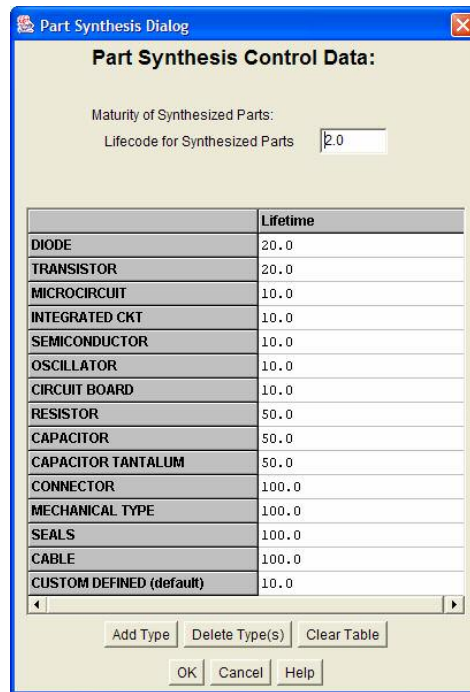
Figure 35. Part Synthesis Dialog window.

All analyses options are listed under the Run pull-down menu shown in Figure 36. The Monte Carlo Multi-Part Analysis uses a system-based analysis to determine the lifetime buy quantities that minimizes life cycle cost for all parts. Demand and supply are treated on a system level. Unavailability or availability penalty is introduced. Individual parts analyses are coupled together. When Monte Carlo is turned On, the solutions given are average values of all distribution solutions.

Similarly, the Partial Monte Carlo Multi-Part Analysis uses the same model as the Monte Carol Multi-Part Analysis simulation, but only performs quantity optimization for parts that have an Initial Qty column (in the Component Dialog Window) value of 0.0 (0.0 is the default). This allows users to run the Monte Carlo Multi-Part Analysis simulation, stop it, record a partial result (by filling in the Initial Quantity column for parts already solved for), and restart the simulation to solve for the remaining parts.

The Verify Results simulation uses the same model as the Monte Carlo Multi-Part Analysis simulation, but instead of performing optimization it gives the end of life cost of user specified (Initial Quantity column in Component Dialog Window) final order quantity. This is just running the cost model for user specified fixed lifetime buy quantity on the parts.

To compute the mean demand quantity for each part (when it becomes obsolete) users must select the Demand Cost simulation. Users can also use a user specified percentage of the demand as a lifetime buy quantity for cost analysis. The user specified percentage is entered in the Simple Policy field in the Solution Control Dialog.

The Sensitivity Analysis performs Monte Carlo Multi-Part Analysis multiple times for a range of inputs. For Simple Policy (only option in the Default mode), the simple policy is ranged in 5 steps from 20 percent less than the entered simple policy to 20 percent more than the entered simple policy.

At anytime, to interrupt the execution of the analysis, users can select the Stop Simulation option.
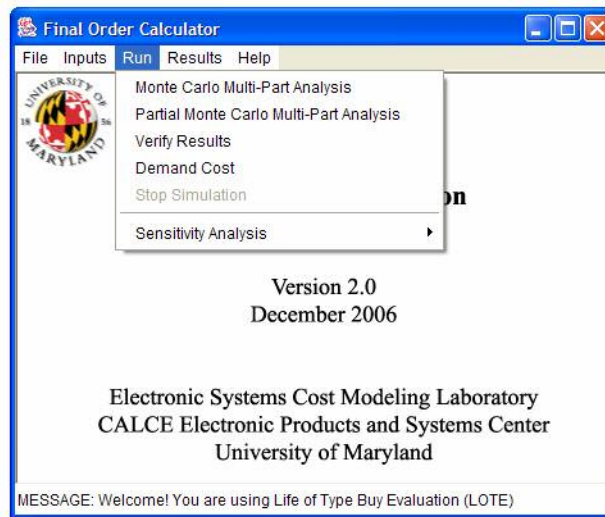
Figure 36. Run pull-down window.

Appendix B – Single Part Case Study Results

The following figures are extended results to supplement Section 3.3.7 Obsolescence Dates. Each Section in this Appendix gives the lifetime buy ratio graphs at 3 different part obsolescence dates (2005, 2012, 2020) with a changing variable (i.e. system unavailability penalty, system availability penalty, holding cost, disposal cost).

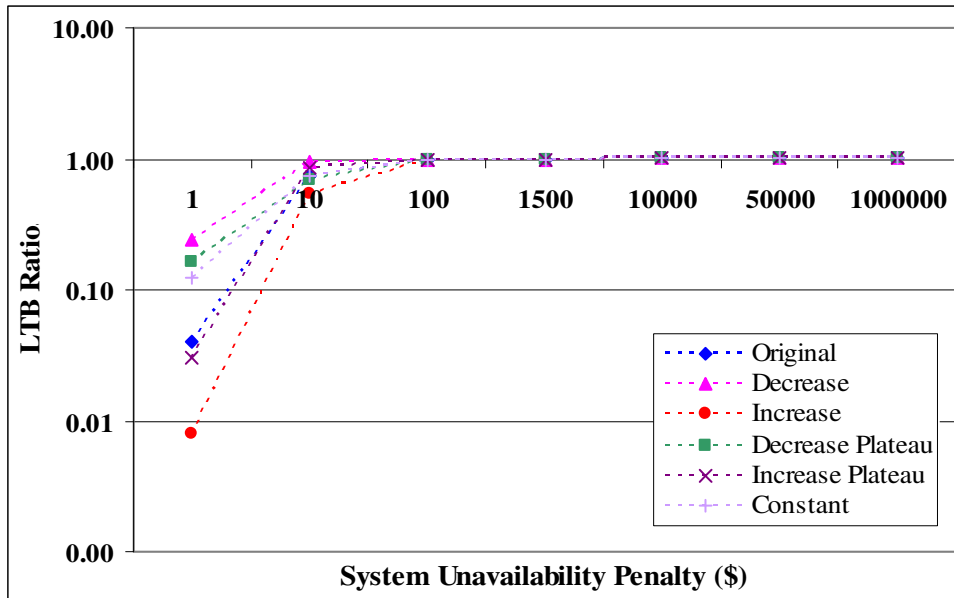*B.1 System Unavailability Penalty Log-Log Graphs*

Figure 37. Graph of LTB ratio at the default setting over varying system unavailability penalty. Obsolescence year is 2005.
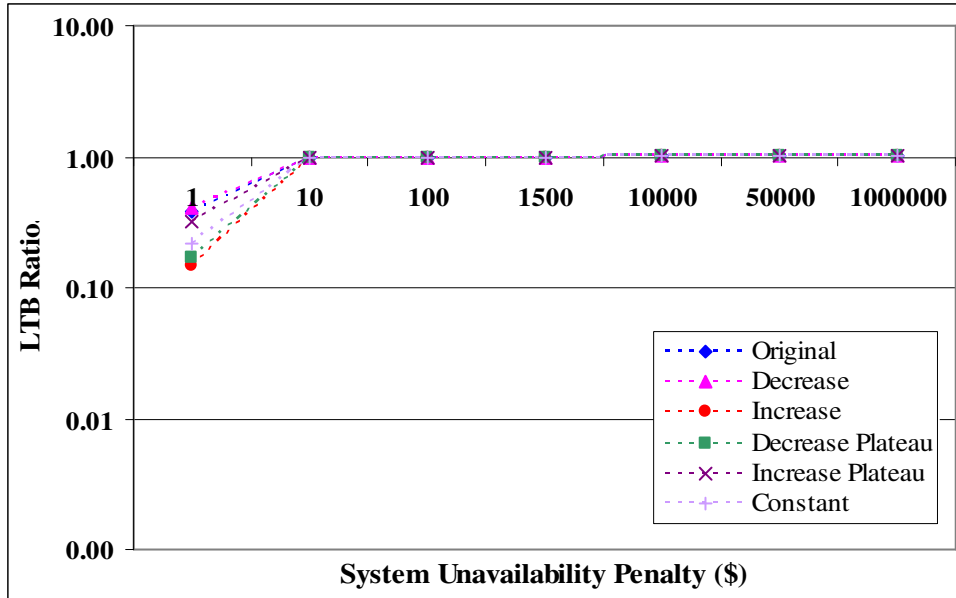
Figure 38. Graph of LTB quantity/ Optimum quantity at the default setting over varying system unavailability penalty. Obsolescence year is 2012.
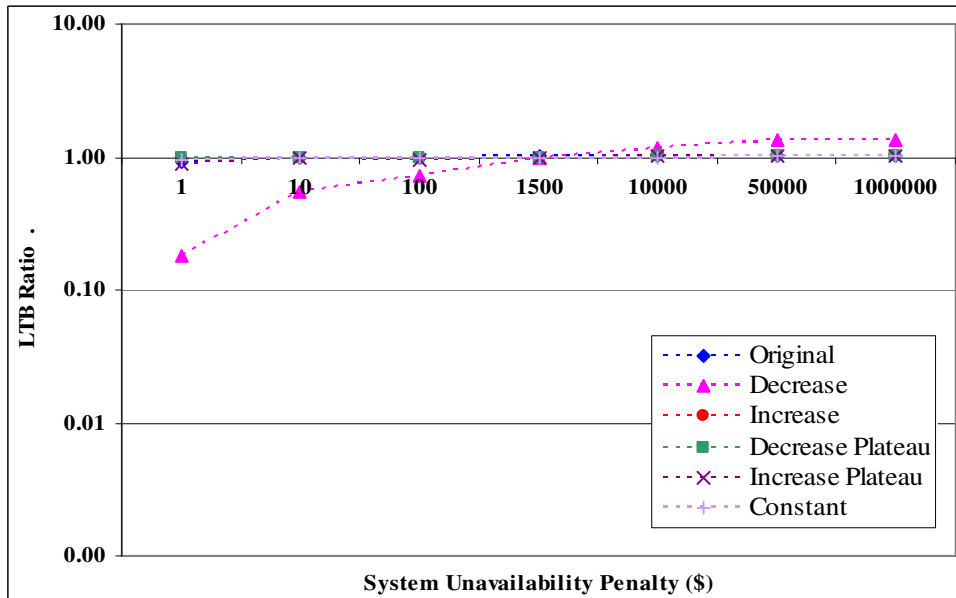
Figure 39. Graph of LTB quantity/ Optimum quantity at the default setting over varying system unavailability penalty. Obsolescence year is 2020.
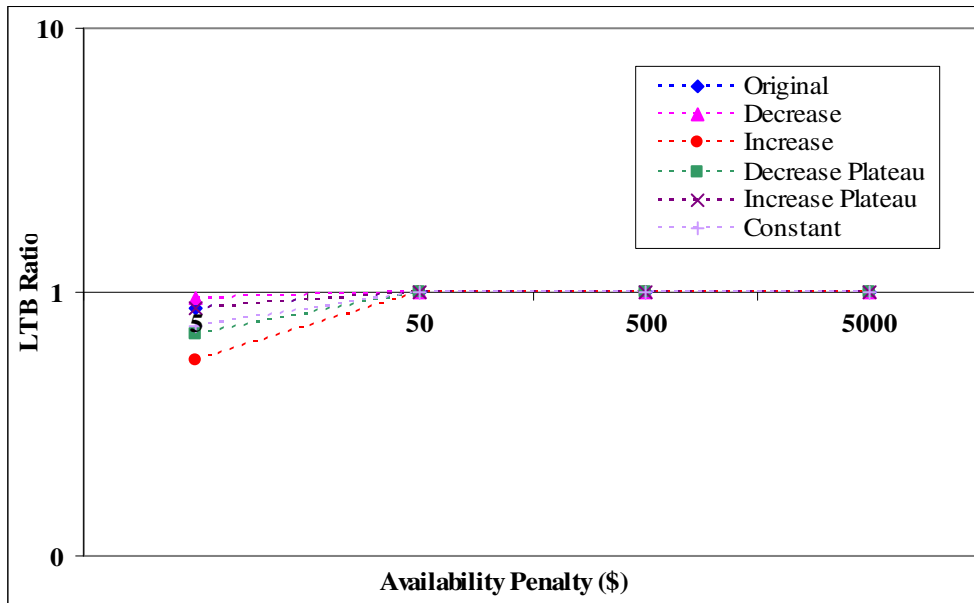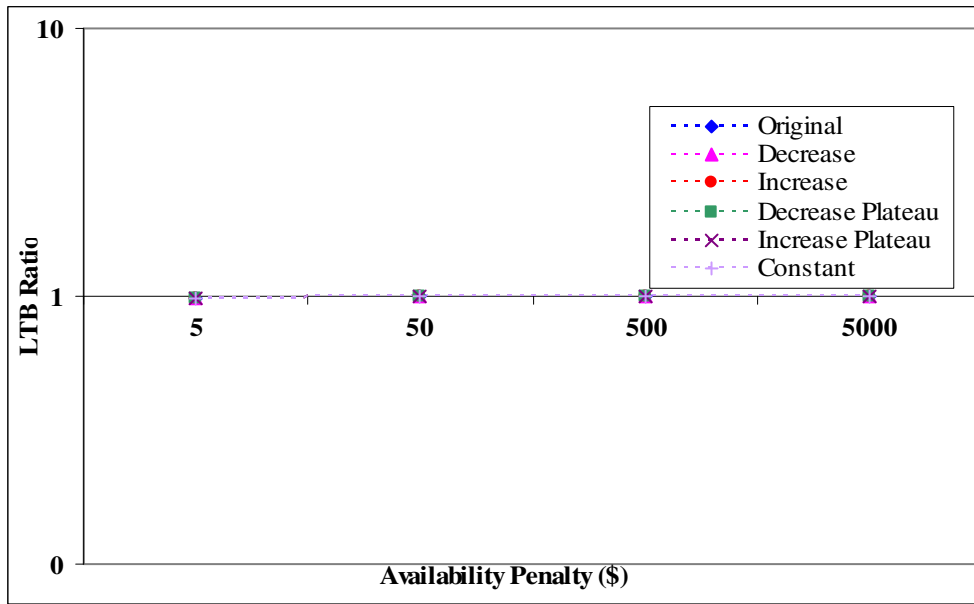
B.2 System Availability Penalty Log-Log Graphs

Figure 40. Graph of LTB quantity/ Optimum quantity at the default setting over varying system availability penalty. Obsolescence year is 2005.
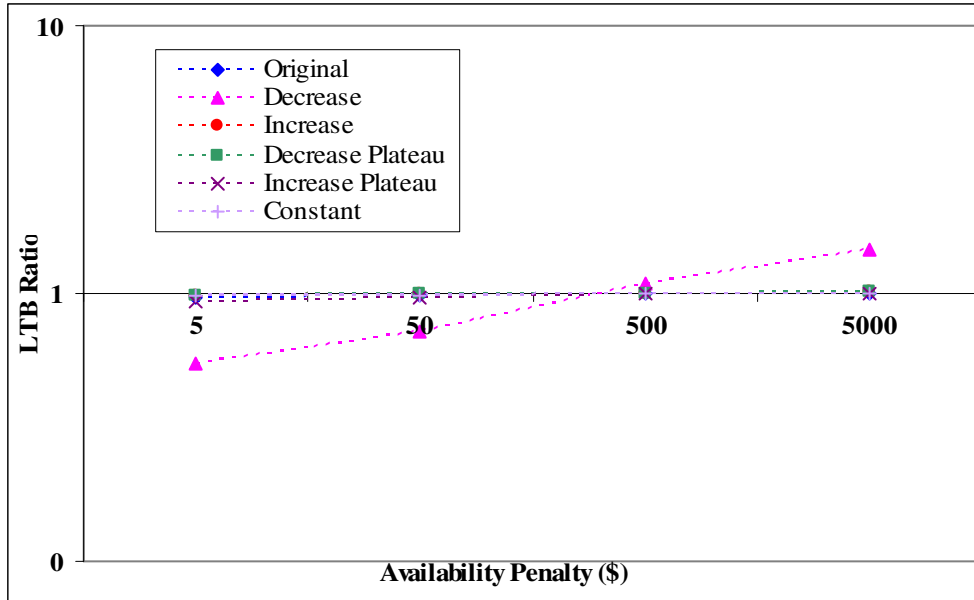

Figure 41. Graph of LTB quantity/ Optimum quantity at the default setting over varying system availability penalty. Obsolescence year is 2012.

Figure 42. Graph of LTB quantity/ Optimum quantity at the default setting over varying system availability penalty. Obsolescence year is 2020.
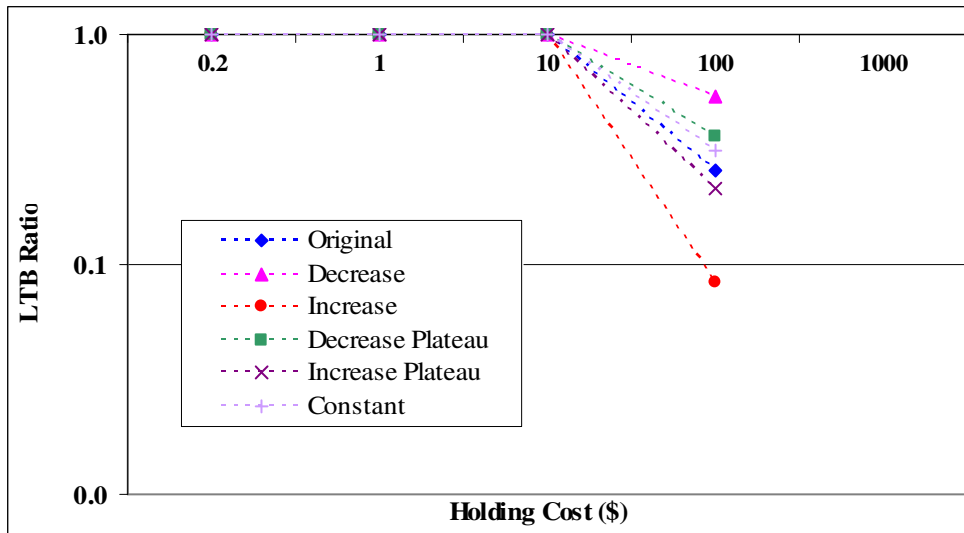
B.3 Holding Cost Log-Log Graphs

Figure 43. Graph of LTB quantity/ Optimum quantity at the default setting over varying holding cost. Obsolescence year is 2005.
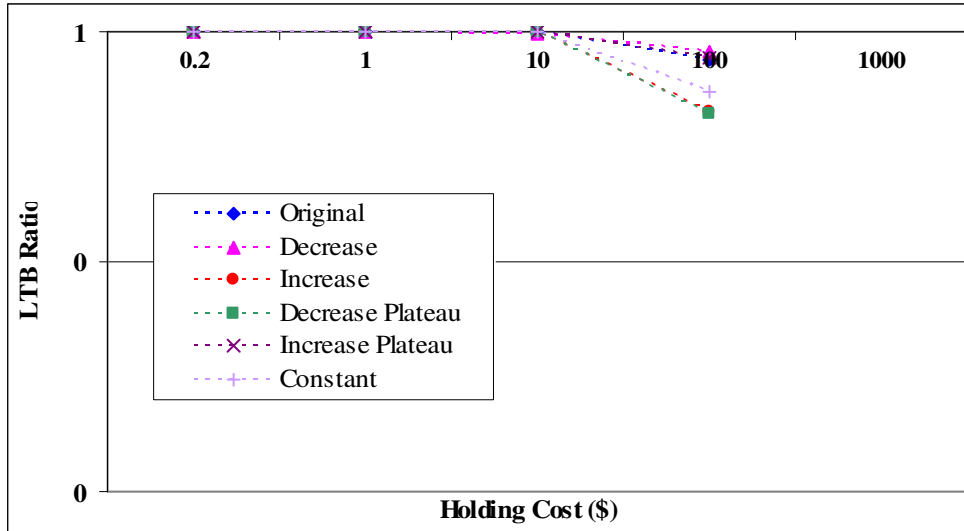
Figure 44. Graph of LTB quantity/ Optimum quantity at the default setting over varying holding cost. Obsolescence year is 2012.
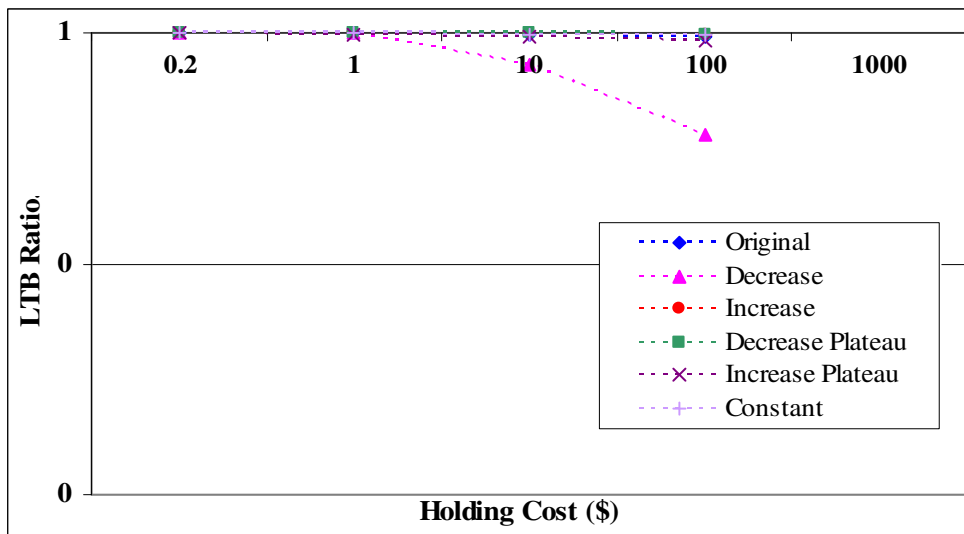

Figure 45. Graph of LTB quantity/ Optimum quantity at the default setting over varying holding cost. Obsolescence year is 2020.
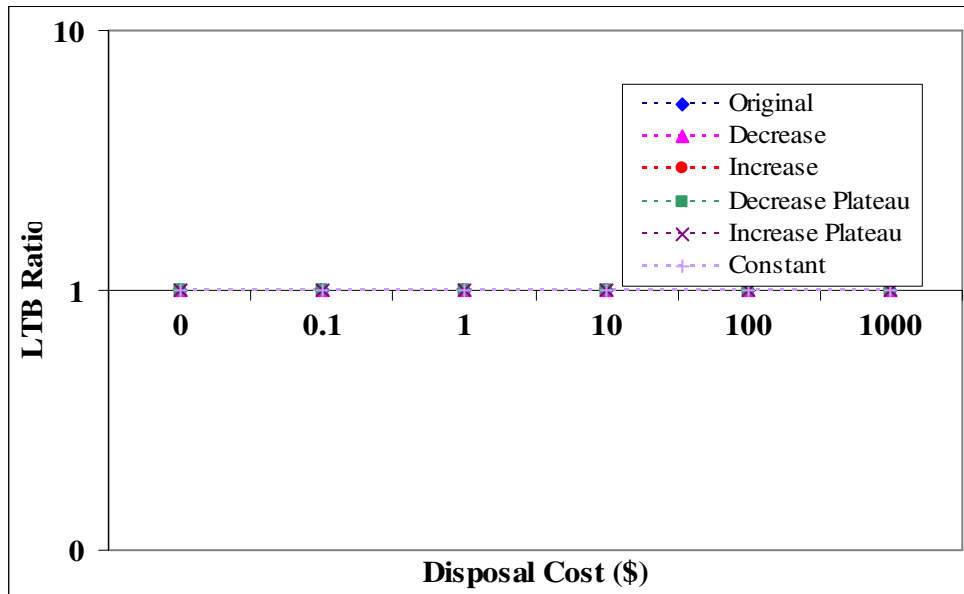
Figure 46. Graph of LTB quantity/ Optimum quantity at the default setting over varying disposal cost. Obsolescence year is 2005.
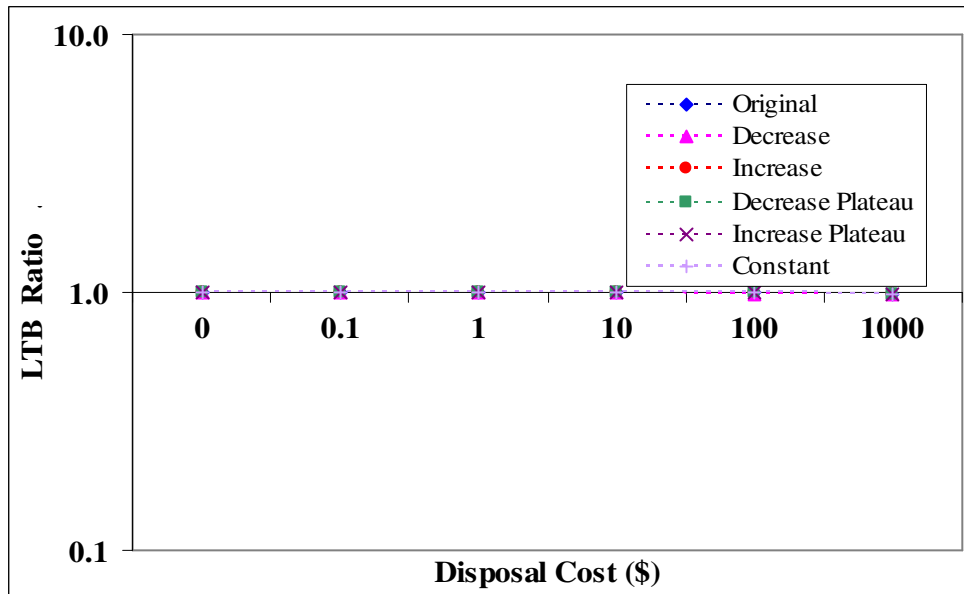

Figure 47. Graph of LTB quantity/ Optimum quantity at the default setting over varying disposal cost. Obsolescence year is 2012.
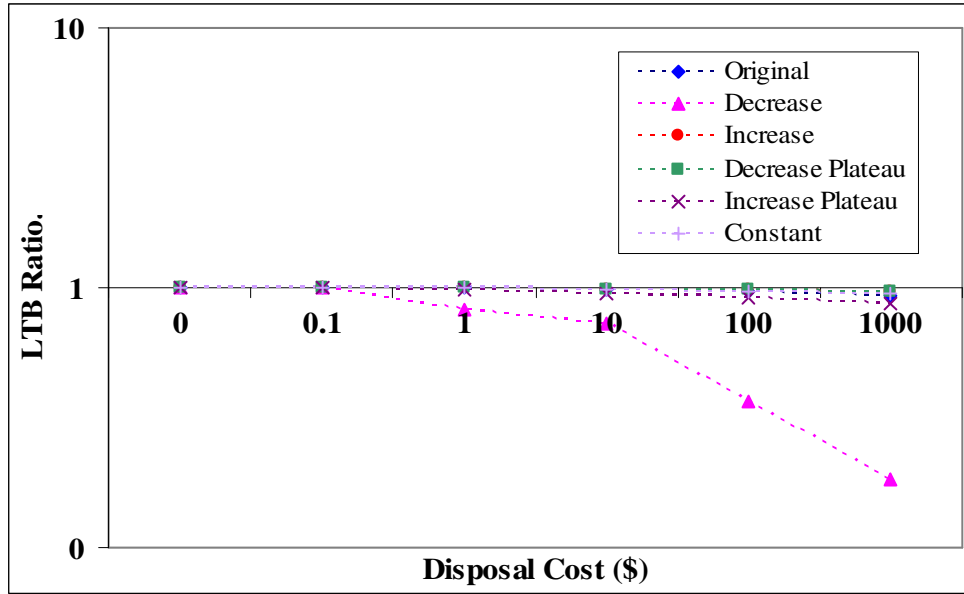
Figure 48. Graph of LTB quantity/ Optimum quantity at the default setting over varying disposal cost. Obsolescence year is 2020.

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