Multi-Echelon Multi-product Inventory Strategy in a Steel Company

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Abstract

This thesis examines a distribution multi-echelon production-inventory system subject to stochastic demand in the steel industry. The sponsor company, Ternium (a South American steel producer), needs to provide short service times under low inventory costs. The goal of this thesis is to generate a model and conclusions to determine where and how much inventory to hold to satisfy a required service level. Risk pooling is an important consideration for this problem; once a steel product advances in the production process, it has less possibilities of use for different customers. Since distribution stochastic multi-echelon inventory systems have no known optimal formulated solution, algorithms and simulation will be used determine a strategy.

The analysis uses simulation as the main method to solve the problem. A distribution multi-echelon model is developed. Different cost scenarios are defined and run. Next, the best set of solutions, defined as the service level–holding cost efficient frontier, is found. To increase the understanding of the problems and provide a better interpretation of the results, we test the sensitivity of the solution and the impact of the input parameters. Later, we explore different ways of solving the problem using alternative modeling methods to determine the base-stock levels. Finally, these solutions are tested with simulation and compared with the best results.

Through the analysis, we find that simulation is a powerful tool for finding the best inventory strategy, but the results are very sensitive to cost parameters. Modeling allows important saving costs if we compare the best solutions found with the simplest policy used by the company (allocating all safety stock to the echelon closest to the customer). Finally, we demonstrate that some of the alternative modeling methods used to allocate inventory perform well, but simulation is an important complement to test and fine-tune these models.

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List of Terms and Acronyms

Echelon	Level in the multi-echelon serial or distribution model. It can be compound of more than one facility.
EF	Efficient frontier.
EIM (or EI)	Echelon inventory model.
EI 99/99/95%	Echelon-inventory strategy model in where echelon 1 provide 99% SL to echelon 2, echelon 2 provide 95% SL to echelon 1 and echelon 3 provide 95% SL to the customer.
EI 99/99/99%	Echelon-inventory strategy model in where echelon 1 provide 99% SL to echelon 2, echelon 2 provide 95% SL to echelon 1 and echelon 3 provide 95% SL to the customer.
ELT	Echelon lead time.
ENRL	Echelon net replenishment lead time.
Facility	Each one of the inventory positions in an inventory system.
FG	Finish goods. Name given to the inventory in the last echelon (3), shape-customized coated steel.
HC	Safety stock Holding Costs.
IT	Information technology.
k_{sim} (or k)	Inventory factor that determine the safety stock at the echelon by multiplying the standard deviation and the square root of the NRL.
LT	Lead time.
L, L, L costs	Cost strategy with holding costs low at the 3 echelons.
L, L, H costs	Cost strategy with holding costs low at echelon 1 and 2, and high at echelon 3.
L, H, H costs	Cost strategy with holding costs Low at echelon 1, and high at echelon 2 and 3
M-E	Multi-Echelon.
M1	Master 1. Name given by Ternium to the work in process at echelon 1, cold rolled steel coils.

M2	Master 2. Name given by Ternium to the work in process at echelon 2, coated rolled steel coils.
MTO	Make-to-order.
NRL	Net replenishment lead time, equal to the service time of the previous echelon plus the lead time of the echelon.
S-E	Single-Echelon.
S-E "i"	SE strategy 1, 2 or 3. They refer to different safety stock allocations among the echelons.
SL	Service Level, percentage of order fulfilled completely from stock.
SS	Safety Stock.
ST	Service Time, committed time to the customer.
t	Tones.
w	Weeks.
σ	Standard deviation of the demand.
μ	Mean of the demand.

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Finally, I want to dedicate this thesis to my father and mother. Especially to my father, who is not with me physically; he taught me with his daily example that everything good in life is reached with work and sacrifice, being always loyal to your principles.

1 Introduction

The objective of this thesis is to solve a problem of inventory placement in the steel production process. In addition, we will analyze the performance of simple models in terms of cost and service level, compared with more sophisticated modeling approaches. This problem involves several characteristics commonly examined in modern supply chain management: multi-echelon inventories, the need for responsiveness, demand complexity, and the possibility of leverage through risk pooling and postponement. The analysis will be based on a steel-making company, Ternium.

1.1 Ternium: the Company and the Problem.

Ternium is a South American steel-making company. It produced 10.5 million metrics tons of steel and generated revenues for $ 8.1 billion in 2007. Ternium employs 18,000 people in its mills, service centers, and commercial offices. Its main mills are located in Argentina and Mexico. Less important plants and service centers are located in the southern USA and Guatemala. In addition, commercial offices are located in USA, Spain, China, México, Argentina, Guatemala, Ecuador, Venezuela and Colombia, and they serve extended markets.

During the last three years, Ternium acquired two Mexican mills. They account for almost the 50% of the Mexican steel market. This market is quite different from the ones initially attended by Ternium, for multiples reasons.

First, total Mexican steel production is not enough to satisfy the domestic market, thus government encourages importation. Mexican customers can easily change from one supplier to other. In Argentina and Venezuela, markets are mainly satisfied by Ternium and it is not attractive to import. Second, Mexican production is mainly dedicated to automotive, home appliance, food canning, and other industries, and most Mexican plants are producing part-time for the US market. These industries have volatile demand and require short service time.

The problem that this thesis will analyze, based on Ternium's Mexican case, is to decide where to allocate the safety stock to guarantee low costs while maintaining the responsiveness that customers need. To do this, we model the complexity of an inventory system with several echelons (a multi-echelon inventory system).

1.2 The Multi-echelon System in Ternium

A multi-echelon inventory system involves a series of inventory facilities linked in any way. An inventory facility is a place in where inventory is held before being moved to other facilities or the final customer. In each facility other activities may be performed and the state of the material may change. Examples of this are assembly and production facilities.

The simplest multi-echelon configuration involves a pair of inventories facilities. For example, it could be a production plant and a distribution center satisfying final customers. More complicated models involve different configurations with more than two facilities. They can be serial chains, where every facility has at most one upstream and downstream facility, distribution chains, where every facility has at most one upstream facility, assembly chains, where every facility has at most one downstream facility, or more general three shape networks. Additionally, they can manage one item or multiple items.

Ternium manufactures a wide range of items: semi-finished, flat rolled, long, welded tubes, beams and rolled form steel products. This study will focus on high-end flat coated rolled products. These are steel products covered with another material (zinc, tin, chrome or organic coatings) primarily for increasing corrosion resistance. Each product involves up to 10 production steps to become a final product. Thus, these products have a long production lead time (between 8 and 10 weeks).

Steel is produced with the particular chemical composition, coating and dimensions, required by each customer. At this moment, the company is managing more than 25,000 items, and the number of upstream items is significantly lower than the number of finished goods items.

The cost of scrapping or resizing unused material for a particular customer is high. Thus material is held upstream as long as possible. However, this strategy conflicts with the desire for low service times and high service levels.

Figure 1.1 depicts the flow that will be use in the rest of the document for this supply chain:

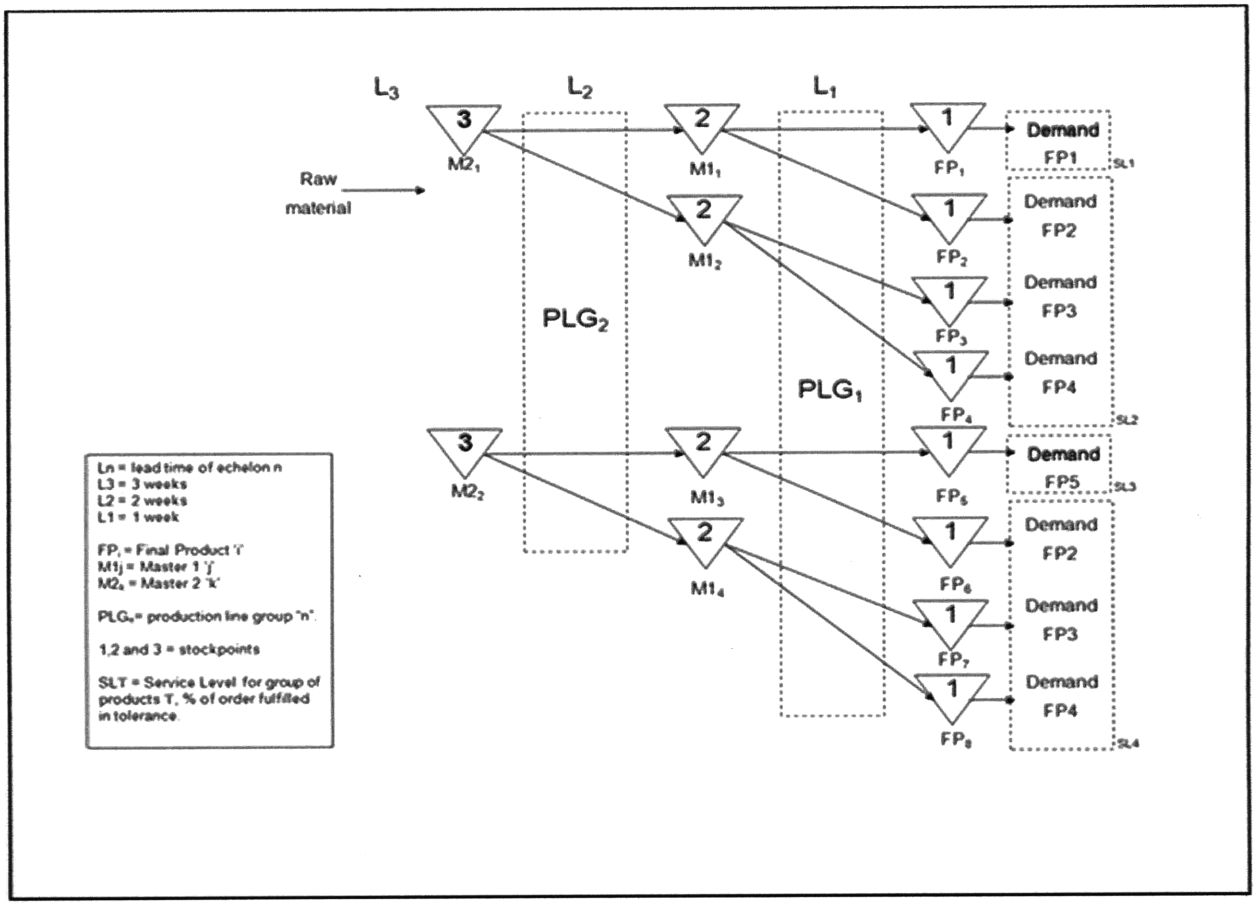


Figure1.1: Description of Ternium's Model

The simplest case is serial network of three echelons; the most complicated can include more facilities in each echelon than the shown example, following the same distribution model. The following list explains the nomenclature used in Figure 1.1.

- Families and Products (M1, M2 and FP)

Three families of products are considered in the picture,

- Master '2' Products (M2): cold rolled coils of steel. These products have a variety of thickness, width and chemical compositions. Other less-important characteristics, such as surface finishing and border type, change too.

- Master '1' Products (M1): coated cold rolled coils of steel. In addition to the characteristics of Master 2, these products add variation in the color, thickness, type, and width of the coating. The main types of coatings are zinc, tin, chrome and organics.
- Final Products (FP): Coated cold rolled strips or sheets of steel.

Each one of these families has a number of products denoted by the sub indexes 'k', 'j' and 'i' respectively. There is a unique relation between each final product (FP) and his Master 1 (M1) and Master 2 (M2). When a product changes families by moving downstream in the process, it is impossible to return it to the previous state.

- Production Line Group (PLG)

Only two groups of production lines will be considered. The first group (PLG1) considers all the lines that coat a cold rolled coil of steel. They are all treated as a single facility with a single lead time. The second group (PLG2) includes a series of lines that are used for cutting the coil in different ways.

- Lead Times, LT (L1, L2 and L3)

There are 3 lead times: raw material to M2, M2 to M1, and M1 to FP. They will be considered fixed for this study. The process time of each coil is short (only a few minutes), but the scheduling rules are complicated and differ from line to line. Set-up costs are usually high with respect to the margins of the products. A decoupling stock adds flexibility to facilitate the scheduling and makes the assumption of fixed lead time reasonable. Each lead time is display in the graph. The scheduling problem will not be considered in this work.

The lead time accounts for the production time and the transportation time. Transportation time between facilities in the factory is almost negligible; thus production time, considered as the time that the decoupling stock needs, will be used as a synonym of lead time in this document.

- Service Level Groups (SL)

Products are separated into groups with the same required service level. The service level is chosen by the management and reflects their understanding of the customers' needs. Each item is rated as 'Fulfilled' if it reaches the quantity required by the order. In this work, most of the studies will be performed with the objective service level (SL) of Ternium, 95%. This service level applies to most of the coated finished products, which are in the scope of this thesis. We also include a sensitivity and trade-off analysis of cost and SL.

Service Time (ST) is the time needed to satisfy an order. This could apply to final goods for customers if we are considering a final echelon facility, or work in process for other facility in the case of levels 2 or 3. Different customers have different required service times, but the scope of this thesis is limited to customers that must be satisfied in the same week that they put their order (ST = 0 week).

1.3 Solution Approach

As was previously stated, the objective of the thesis is to determine where to hold inventory in order to minimize costs, reach the required service time, and accomplish the desired service levels. Because there are more than 25,000 items, an individual solution for each item is too large of a problem and is not practical for Ternium. Thus the goal is to develop a practical model and conclusions that can be applied to families of items.

The analysis will be performed over a selected set of products provided by Ternium, which are considered representative of the problem. The distribution multi-echelon problem does not have a known optimal solution, so different analytical and simulation models will be used.

2 Literature Review

The multi-echelon problem presented in this thesis is analyzed from two perspectives: one quantitative and the other qualitative. We review relevant literature review on both topics in this chapter.

For the quantitative analysis, three different models are applied based on: single-echelon inventory theory, multi-echelon inventory theory and simulation. The single-echelon inventory theory used considers stochastic, independent and constant demand with an infinite planning horizon and periodic time review. Literature on this topic is presented in Section 2.1. The multi-echelon inventory theory applied extends this to consider multiple inventory locations, and is discussed in Section 2.2. Finally, a simulation model is developed to find optimal solutions and compare the results produced with the other two methods. Simulation modeling literature is discussed in Section 2.3.

The qualitative analysis is based on the concepts of postponement and risk-pooling. Additional factors, such as life cycle, information management and product design characteristics, which are not included in the analytical model, are discussed. We review relevant literature on those topics in Section 2.4.

This thesis work will give an analysis of the results of these three different quantitative methods for Ternium's system, and will also evaluate them in terms of service level, holding cost and calculation complexity.

2.1 Single-Echelon Models

The single-echelon inventory model used to analyze the different sections of the multi-echelon system was taken from Silver, Pike and Peterson (1998). It considers the particular case of stochastic and constant mean demand, periodic review policies and infinite horizon of time.

In particular, the model used is a base-stock inventory policy. These models are called "R,S" models. "R" represents the particular review period of time and "S" the base-stock level. Every period of time "R", an order is sent to the supplier to get back the inventory level to "S". The "S" level is big enough to supply demand during the period of time R + LT, where R is the review period and LT is the supply lead time. The minimum inventory level, called safety stock, is observed at time "R_i + LT", where "R_i" is any review point. Safety stock is calculated using:

,

$$SS = k \times \sqrt{R + LT} \times \sigma \qquad \text{(Eq.2.1)}$$

where

- k, is the safety stock factor, related to the service level required,
- σ, is the standard deviation of the forecast error or of the demand.

Finally, S is calculated using:

$$S = \mu \times R + SS, \qquad \text{(Eq.2.2)}$$

where

- μ, is the average demand per unit of time.

When a single-period problem is solved, the model is referred to as a "newsboy". In the "newsboy" model, final inventory cannot be carried forward. In this thesis, the "R,S" model is employed for different inventory positioning strategies. It will be described in Section 3.3.1.

2.2 Multi-echelon Models

This section describes three different multi-echelon models. The first model was presented by Clark and Scarf (1960). It is included because it gives a theoretical base for the other models and it is the origin of the multi-echelon inventory theory. The second model is a echelon-inventory model introduced by Simchi-Levi et al. (2008) and is used as the base multi-echelon model in this thesis. The last model is a dynamic-programming model introduced by Graves and Willems (2000). It is described because it will be used to verify the simulation model.

2.2.1 Clark and Scarf Model

Clark and Scarf (1960) provided a seminal analysis multi-echelon inventory analysis in their paper, "Optimal Policies for a Multi-Echelon Inventory Problem." They introduce the concept of echelon inventory and the idea that base-stock policies give optimal results in serial multi-echelon inventory problems. A serial multi-echelon model is a system in where every facility has no more than one supplier and one consumer echelon link to it.

Echelon stock at a particular echelon of a chain is defined as the inventory on hand on this echelon plus the entire downstream inventory that in the rest of the chain, including the in-transit material. Figure 2.1 shows the notation used to explain the concept of echelon stocks and echelon positions for a 2-echelon example, taken from van Houtum (2006):

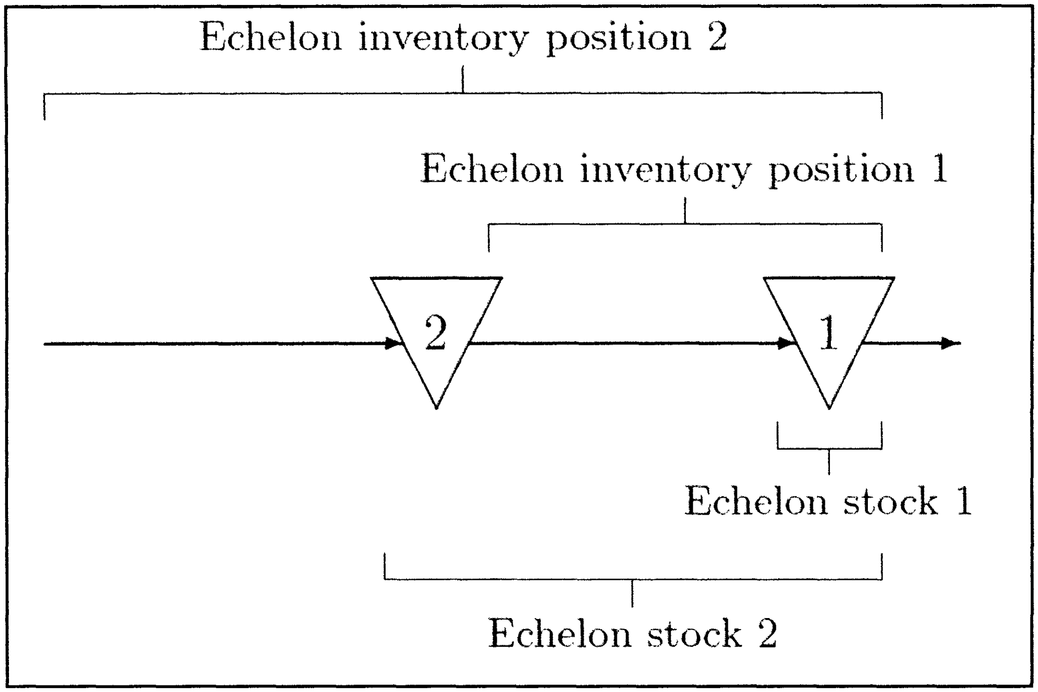


Figure 2.1: Echelon Notation

Echelon inventory positions differ from echelon stock. “Echelon inventory position 1” includes the inventory on-hand in position 1 (“Echelon stock 1”) plus the inventory in transit between facilities 1 and 2. For echelon 2, “Echelon stock 2” includes the on-hand inventory in facilities 1 and 2 plus the transit inventory between facilities. The “Echelon inventory position 2” adds echelon stock 2 plus the material in transit to echelon 2.

Additionally, holding costs per unit per period at each echelon are defined as the incremental cost above the immediate upstream echelon’s holding cost. This is different from the classical single-echelon inventory theory, where the holding cost at any location is considered an independent value.

Other assumptions include:

- The last echelon is the only one that serves the demand.

- There are no ordering costs and the holding costs are linear (defined as explained in the previous paragraph).
- The last echelon has a constant shortage cost per unit per period.
- If the demand not satisfied from stock in a given period, is backordered.
- The demand is stochastic.

Clark and Scarf prove that an optimal solution for this problem is achieved through a base-stock policy, and that it can be calculated by splitting the model into separated problems, each one linked using the echelon stock concept and the backordering penalty. For an n-echelon serial system, the solution comes in the form of "n" Newsboy's equations.

As an example, the Newsboy equations for the two-echelon system shown in Figure 2.1 are given below (van Houtum, 2006).

For echelon 1, the optimal base-stock level S_1 is such that

$$P\left\{B_0^{(1)} = 0\right\} = \frac{p + h_2}{p + h_1 + h_2} \qquad \text{(Eq.2.3)}$$

with

$$B_0^{(1)} = (D_{t_0+l_2, t_0+l_2+l_1} - S_1)^+ \qquad \text{(Eq.2.4)}$$

For echelon 2, the optimal base-stock level S_2 must satisfy

$$P\left\{B_0 = 0\right\} = \frac{p}{p + h_1 + h_2} \qquad \text{(Eq.2.5)}$$

with

$$B_1 = (D_{t_0, t_0+l_2-1} - (S_2 - S_1))^+ \qquad \text{(Eq.2.6)}$$

$$B_0 = (B_1 + D_{t_0+l_2, t_0+l_2+l_1} - S_1)^+ \qquad \text{(Eq.2.7)}$$

where

- S_i*: base-stock level at echelon "i",*
- p *: penalty cost,*
- h_i*: holding cost at echelon "i",*
- $D_{a,b}$*: demand from time "a" to time "b",*
- t_0*: initial time,*
- l_i*: lead time at echelon "i",*
- B_0*: shortfall or backlog at echelon 1,*
- B_1*: shortfall or backlog at echelon 2.*

Clark and Scarf conclude their paper by extending their solution to distribution problems. They show that a base-stock solution solving the problem in steps, as was the case for the serial system, does not lead to an optimal result. A more restricted problem, using "balanced assumptions", is solved. The restricted problem assumes that the inventories in the downstream echelons are almost balanced or that inventory can be moved among positions in the same level.

2.2.2 Echelon-Inventory Model

This model is presented by Simchi-Levi, Kaminsky and Simchi-Levi (2008), and is based on the concept of echelon-inventory. It is an integral model. It is called integral because it considers the system as a whole, as opposed to the single-echelon models, which consider each location individually. Demand is considered stochastic with a constant mean. The model uses a base-stock inventory policy and periodic review.

The echelon inventory at every echelon considers the complete downstream system from that echelon to the final customer. This is similar to the approach developed by Clark and Scarf which was proven to generate optimal solutions for a serial multi-echelon model. The echelon-inventory model assumes total fulfillment of demand between echelons. In contrast, the Clark and Scarf model considers shortfalls among facilities and solves the problem by iterating between adjacent echelons.

In spite of this total-fulfillment approximation, the echelon-inventory model is reputed to give good results for inventory-level solutions. The inventory at each echelon is calculated as the difference between that echelon inventory and the previous one. The calculations are explained in detail in the Method Section, 3.3.2.

2.2.3 Graves-Willems Model

In their book "The Logic of Logistics", Simchi-Levi et al. (2005) present equations that define general distribution systems and explain that solving them is a challenging non-linear optimization problem. They refer to different papers for solutions; one of them is that of Graves and Willems (2000).

In their paper, Graves and Willems present a methodology to solve spanning tree inventories problems under bounded and stochastic demand. They assume that demand can be limited to some maximum values (bounded) and under this assumption an algorithm is developed. The model uses base-stock policies, as the previous two models did. The optimization process involves changing the service time of every echelon and keeping the committed service time to the customer as a constraint. Holding cost is then minimized using dynamic programming algorithm. In this thesis, this model will be used to perform verification of the simulation model.

2.3 Simulation Modeling

This thesis uses an Excel simulation model to represent a distribution multi-echelon system. Two topics about simulation are discussed in this section: basic concepts about the modeling process, and base-stock level multi-echelon simulations.

Winston (2004) describes the basic steps in the simulation process. He explains: "The simulation process consists of several distinct echelons. Each study may be somewhat different, but in general, we use the following framework:

1. Formulate the Problem.
2. Collect data and develop the model.
3. Computerize the model.
4. Verify the computer model.
5. Validate the simulation model.
6. Design an experiment.
7. Perform the simulation runs.
8. Document and implement."

This is the scheme followed in this thesis to construct and use the simulation model. Additionally, some concepts from Hillier and Lieberman (2005) were considered, especially their "Plan, Build, Test, Analyze" approach applied to model building. This approach gives a framework to the previous eight tasks. The "Plan" step involves the analysis of the process of the multi-echelon system. The "Build" step involves the software programming. The "Test" step involves the verification and the validation; that is to test the model to understand if the results are correct, and then to understand if the results are realistic for the Ternium problem. The “Analyze” step includes the final data analysis and conclusions.

Research was also conducted on simulations specific to multi-echelon processes. Detailed information in the manuals of the simulation software “BaseStockSim”, Snyder (2006), and the optimization software “Power Chain Inventory Academy” was used to understand the precise ordering of the steps and to be able to construct the logic of the model. This information was complemented with ideas of the book “Matching Supply with Demand” (Cachon and Terwiesch, 2008), which describe in detail the chain of steps followed in a base-stock model. These three sources were integrated to generate the following steps for the model:

1. Receive orders.
2. Place orders to suppliers.
3. Begin production of the period.
4. Backorder, if it is necessary.
5. Release produced material that has completed its production lead time.
6. Satisfy demand.
7. Account applicable holding cost.

These steps need to be coordinated every period among all the echelons in a synchronized way.

2.4 Additional Considerations

Postponement and risk-pooling are two concepts directly related to strategic inventory deployment; that is, deciding where and what kind of inventory to allocate to each echelon of a multi-echelon system. Both concepts are applicable to this thesis.

Pagh and Cooper (1998) introduce a framework to decide when to 'speculate' (choose) and when to 'postpone' logistics and manufacturing decisions. Their framework considers product, market and demand, and manufacturing & logistics variables to determine the final strategy. Essentially, postponement involves delaying the change of the material state. For Ternium's system, this means holding material upstream, prior to differentiating the final product type.

Risk pooling is a related concept. As Taylor (2004) states: "The idea behind risk pooling is to combine the management of inventories that would otherwise be controlled separately so that variability in demand can be handled with less safety stock." If demands are independent, the standard deviation of the aggregated demand will decreased compared with the sum of independent standard deviations. Thus, less safety stock is necessary to provide the same service level as when products are not aggregated.

Some other concepts, such as life cycle, product characteristics, relative value, non-constant demand, and economies of scale are considered. Life cycle refers to the item's lifetime demand curve. It is related to technological change, market acceptance and the easy of competitive entry. The main echelons of this cycle are: development, growth, shakeout, maturity and saturation (Silver et al., 1998). Product characteristics refer to the design of the product and its possibility of postponement. Relative value refers to the change in the item cost when it is transferred and manufactured throw the process. Non-constant demand involves demand with high coefficient of variation or changing mean. Finally, economy of scale refers to the item cost savings related to increase production or transportation quantities. These concepts will be used in this thesis to complement the numerical analysis in the final recommendations for inventory strategy.

3 Methods

This section presents the methodology applied to answer the main questions of this thesis: where should inventory be held in Ternium's supply chain, and can simple methods lead to good economical results in this multi-echelon problem? In addition, we propose to explain how customer service level, inventory holding costs and percentage of bounded demand affect the solution.

To reach these objectives, we present the methodology for the three different categories of inventory models used: analytical single-echelon, analytical multi-echelon and simulation. These models represent respectively decentralized, semi-centralized and centralized decision-based inventory models. Before presenting the models, we introduce the symbols used to represent the multi-echelon system in this thesis.

3.1 General Comments about Symbols

To simplify the graphics, the distribution system will be shown as serial models (see Figure 3.1). Thus echelon 1 and 2 in the simplified graphics will represent more than one facility in reality.

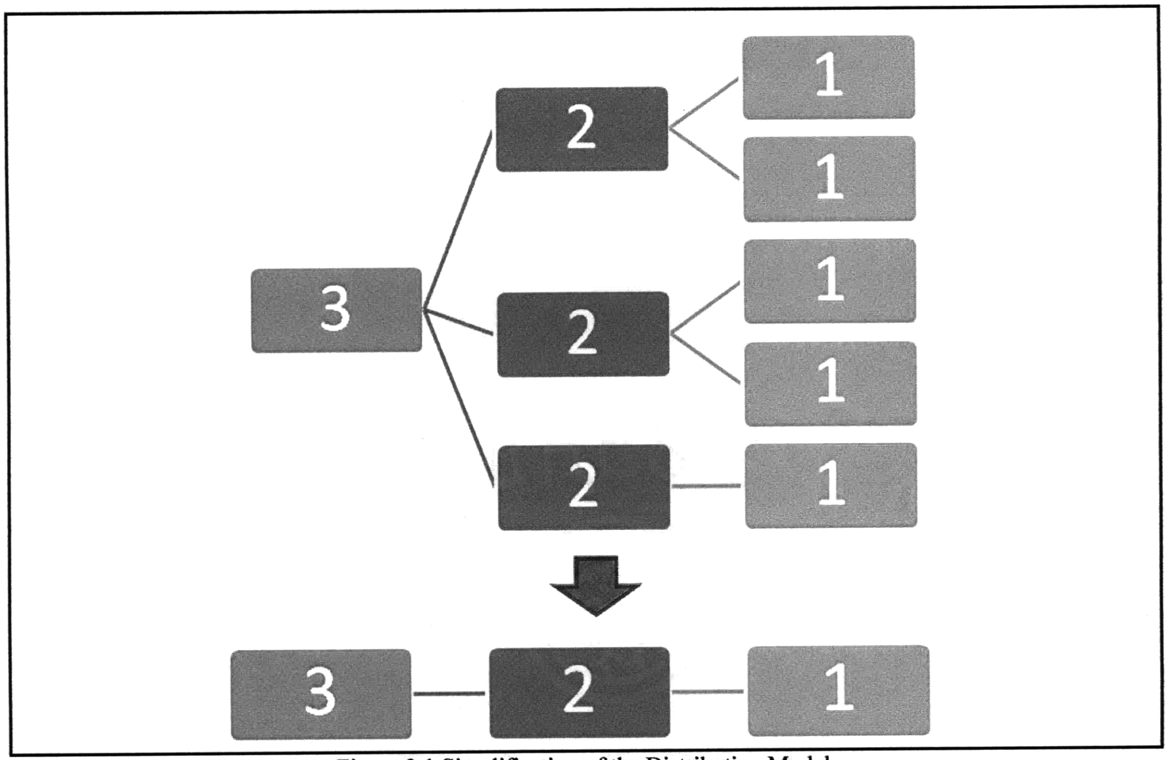


Figure 3.1 Simplification of the Distribution Model

Additionally, each one of the echelons may have internal symbols in some figures. They will represent the existence of transportation and/or production functions (mandatory) and inventory safety stock (optional).

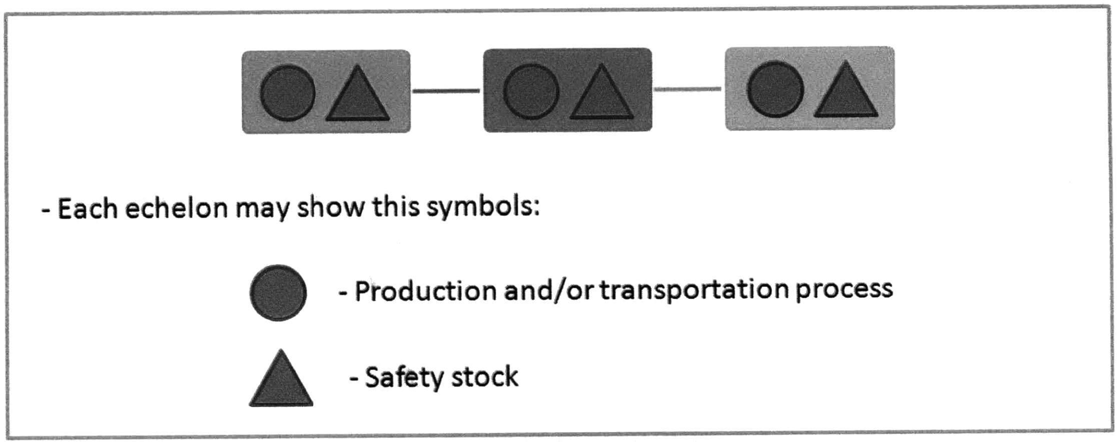


Figure 3.2 Model Symbols

3.2 Introduction of the Models

All the models use base-stock inventory policies. The base-stock level is set at each echelon and it remains stable. Every time that a echelon receives demand from customers, or other echelons, an order equal in value is sent to the previous facility to restock the inventory position level to the base-stock inventory level.

This base-stock level can be calculated with different grades of decision-centralization. In a decentralized decision model, the inventory level is fixed without considering the impact of the previous and subsequently facilities. That is, single-echelon inventory models are applied at each echelon individually. This is described in Section 3.2.1.

Next, a semi-centralized decision model is used. This is an approximation to a centralized decision model applying the concept of inventory-echelon stock. This is explained in Section 3.2.2.

In a centralized decision models the base-stock levels is set considering the complete chain. We will use either the Graves-Willems model or a simulation model that we constructed to find these base-stock levels (Section 3.2.3 and 3.3 respectively).

Figure 3.3 shows the lead time data used for the analysis of the decentralized and semi-centralized decision model. The service time that every echelon quotes depends on the inventory strategy used.

Description	Echelon 3	Echelon 2	Echelon 1	Total
ST_{n-1}	0			
LT_n	3	2	1	6
ELT_n	6	3	1	--
ST_n				0

UNITS IN WEEKS.
$ST_{n-1:}$ service time of the previous stage (n-1)
LT_n : Product Lead Time of stage n
$ST_{n:}$ service time provided by stage n
ELT_n: echelon process time at stage n

Figure 3.3 Model Lead Times

The service time (ST_n) in column "Total", 0 weeks, shows the agreed on delivery time with the customer. ST_n is left blank in echelons 1 and 2 because it will depend on the inventory strategy used in the system.

3.2.1 Decentralized Policy: Application of Single-Echelon Model

Single-echelon theory is applied to three different strategies for allocating safety stock:

- SS (safety stock) as close to the customer as possible (Scenario 1)
- SS concentrated in the intermediate position (Scenario 2)
- SS as far from the customer as possible (Scenario 3)

Figure 3.4 shows how safety stock is deployed in each strategy. Triangles show the existence and relative volume of the safety stock in each facility.

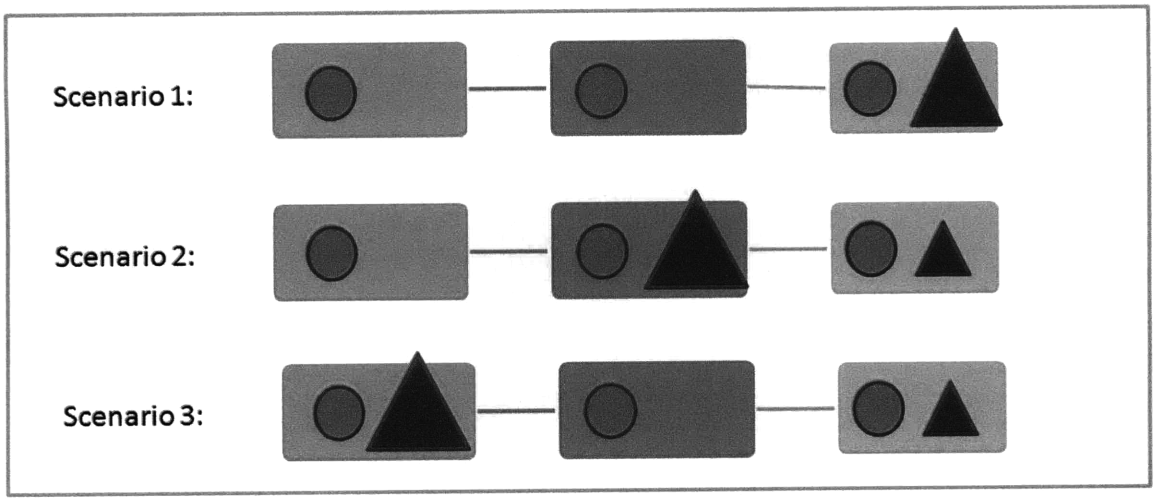


Figure 3.4: Single-Echelon Inventory Strategies

In order to calculate the safety stock, we assume demand is normally distributed with a constant mean; this assumption is discussed in Section 4.2. Normal demand can be described by its mean (μ) and standard deviation (σ). Under these assumptions, the safety stock (SS) that each echelon holds is (Simchi Levi et al., 2008):

$$SS_{ij} = k_i \times \sqrt{NRL_i} \times \sigma_{w_{ij}} \qquad \text{(Eq. 3.1)}$$

where:

- k : service level factor,
- NRL: net replenishment time, $ST_{n-1}+PT_n$,
- σ_{wij}: weekly (*w)* aggregated demand standard deviation,
- i: echelon level,
- j: number facilities in the level.

Table 3.1 shows the values of "k" for this case ("Single-Echelon"). The second column shows the safety stock value, the third the fulfillment probability. Columns four and five are used in the next section.

Table 3.1: Safety Stock Parameters. "Equiv. S-E SL": Equivalent Single Echelon Service Level. "Value": safety stock factor. "Equiv. S-E SL": probability of fulfillment

	Single-Echelon		Multi-Echelon	
	Value	Eqiv. S-E SL	Value	Eqiv. S-E SL
k1	1.64	0.95	1.64	0.95
k2	1.64	0.95	2.33	0.99
k3	1.64	0.95	2.33	0.99

These 'k" factors are chosen from statistical normal tables and set the probability of stock out of the system equal to 1 minus the service level (1 – SL). "1-SL", in the previous table, is included in column three and five. For example, the k1 for the single-echelon model is 1.64 and it guarrantees a service level of 95%.

In the single-echelon models, k values are set to warranty the committed service level, 95%. In the case of the echelon-inventory model, the first echelon SL is set at 95%, but echelon 2 and 3 to 99% to generate a close to no stock-out situation for the first echelon. In addition to this scenario (95%, 99%, 99%) this model is run with a "99%, 99%, 99%" k-values safety stock strategy. The run scenarios are explained in Chapter 4.

3.2.2 Semi-Centralized Policy: Echelon-Inventory Model

First, safety stock is calculated for every echelon stock. Echelon stock includes the entire inventory from that echelon plus all inventories downstream towards the final customer, as defined using Figure 2.1 in Section 2.2. This analysis is made using the aggregated demand of all the echelons downstream of the analyzed echelon and the total lead time from the analyzed echelon to the customer (service time plus included production lead times).

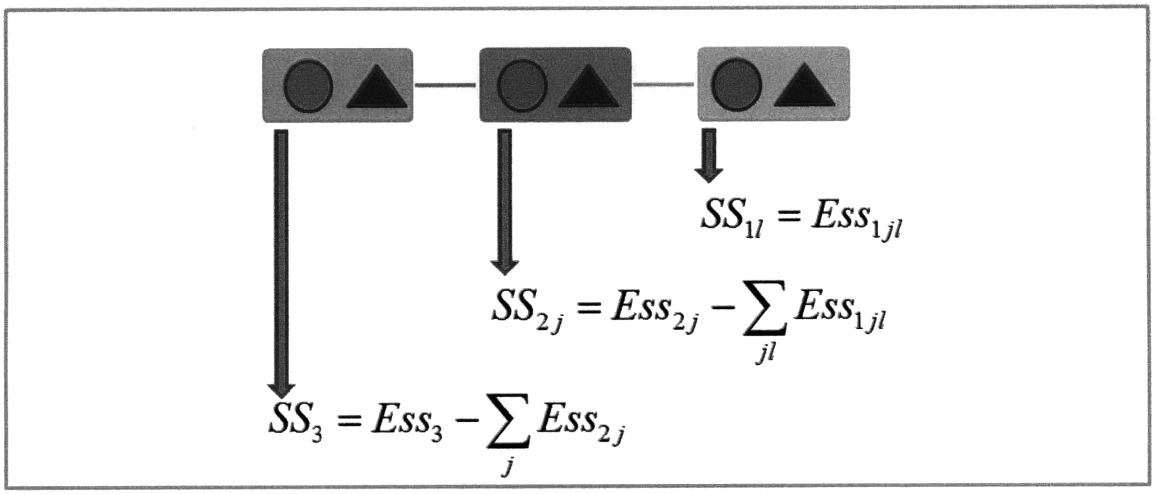
The safety stock of each echelon (E_{ss}) is calculated using:

$$Ess_{ij} = k_i \times \sqrt{ELT_i} \times \sigma_{ij} \quad ; \quad i = 1,2,3 \qquad \text{(Eq. 3.2)}$$

where

- k_i are the values of Table 3.1, columns four and five,
- ELT_i: echelon production time as $\sum_{k=1}^{i} PT_k$,
- "j" depends on the number of facilities at every level of the system.

Second, we calculate the safety stock at every echelon. Safety stock at echelon 1 is equal to safety stock at echelon 1. In the next echelons, each safety stock is calculated subtracting the echelon safety stock of the previous echelon from the echelon safety stock of the analyzed echelon. Figure 3.5 explains this graphically.



$$SS_{1l} = Ess_{1jl}$$

$$SS_{2j} = Ess_{2j} - \sum_{jl} Ess_{1jl}$$

$$SS_3 = Ess_3 - \sum_{j} Ess_{2j}$$

Figure 3.5: Simplified Multi-Echelon Model SS Calculations

Data on lead times was shown in Figure 3.3.

3.2.3 *Centralized Policy: Simulation*

Two centralized decision models are used. The first one is the Graves-Willems model, described in this section; the second one is a constructed simulation model covered in Sections 3.3.

The Graves-Willems model is run with the student version of "PowerChain Inventory 3.0" provided by the company Optian. The model was built and run for the selected items in this thesis. Figure 3.6 shows the system. The number in each facility represents the production lead time.

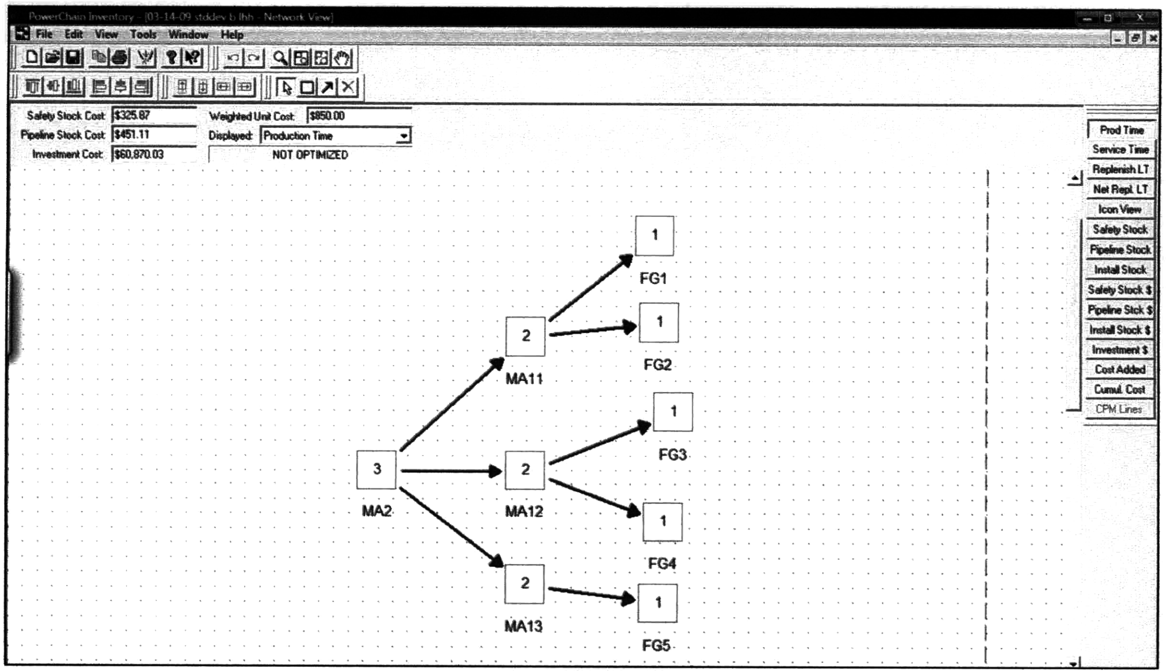

Safety Stock Cost: $325.87
Pipeline Stock Cost: $451.11
Investment Cost: $60,870.03
Weighted Unit Cost: $850.00
Displayed: Production Time
NOT OPTIMIZED

Figure 3.6: PowerChain Inventory 3.0

In additional to the production time, the following data is required:

- Customer demand (mean and standard deviation),
- Customer service time,

- Holding cost per period (as a percentage of the unit cost),
- Unit cost at every echelon.

The model assumes independent demand and a customer service level of 95%. It optimizes the system with respect to the safety stock holding cost by changing the service time of every echelon.

3.3 Development of the Simulation Model

The simulation model explained in this section is run for a range of safety stock allocations. The safety stock allocation calculated using the models discussed in the previous sections (3.2.1 to 3.2.3) will be compared against them.

3.3.1 General Considerations

The simulation model is developed to represent a distribution model of six shape-customized coated final products (FP), three intermediate coated products (M1) and one uncoated mother item (M2). The notation and the general description of the steel process are included in Section 1.2. Some of the runs are made with less than six final products, depending on the example selected.

The model was developed in Excel, and special consideration was devoted to the logic, and then to the construction of the model. Since it is a centralized decision model, the relations among the echelons were carefully considered. Significant time was dedicated to the programming of the model and, later, to the verification. Finally, it logic was validated with the personnel of Ternium.

3.3.2 Model Logic

In order to simulate the logic of a base-stock model, each echelon follows the following steps:

1. Receive orders.
2. Place orders to suppliers.
3. Receive material and begin production of the period.
4. Backorder whenever necessary.
5. Release produced material that has completed its production lead time.
6. Satisfy demand.
7. Account applicable holding costs.

In the centralized model, all the echelons receive the same demand information at the same time, since information is fully communicated throughout the system. This is shown in the next figure as the reception and transference of orders (and demand) in the three echelons. Next, every echelon receives work in process from the previous echelon and initiates its own production. If work in process completes the production lead time it is released as on-hand inventory. Finally, internal or external demand is satisfied. If the final available material is not enough to satisfy an order, the unfilled demand is backordered and considered as extra demand for the next period. This means that the next period of time, the echelon will try to satisfy the new demand and the backordered demand. This process must be synchronized among the 3 echelons; this is accomplished through the replication of the demand and the transference of material, as is shown in Figure 3.7.

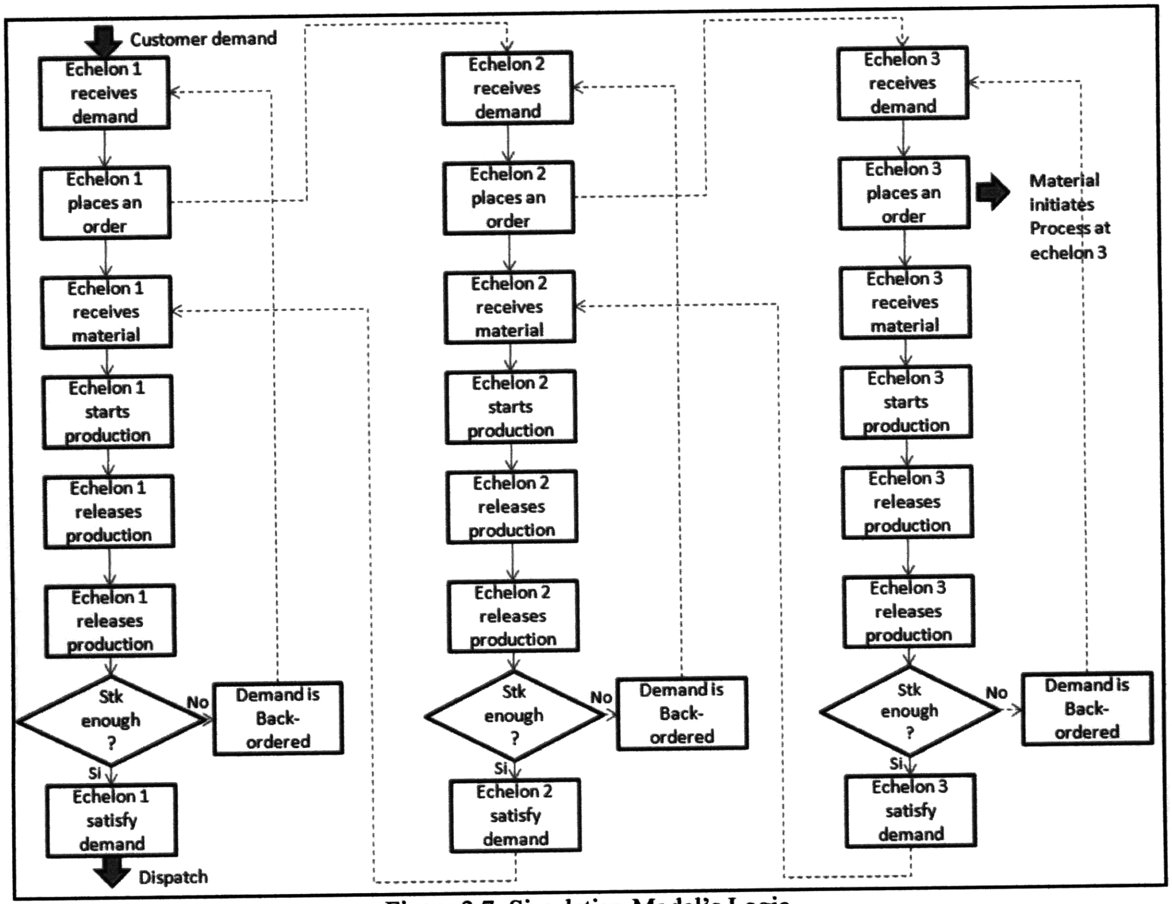


Figure 3.7: Simulation Model's Logic

3.3.3 *Model Development*

Based on the previous logic, we developed a dynamic stochastic discrete simulation model. It is dynamic because it represents the systems as it evolves over time. The model will run every scenario for 1,000 weeks and the system state changes after every period. The model is stochastic because the driver variable, the demand, is a random variable. It is generated using Monte Carlo sampling. The data used to characterize the demand was taken from Ternium's actual data. It is discrete because it represents the system variables only at the end of fixed period of time. The model is simulated at intervals of one week. Initial inventory levels are set without the receipt of material at the beginning of the simulation (point (3) in the series of steps at the beginning of Section 3.3.2).

The system variables are each echelons' inventory levels and the back-ordered demand at the end of each period. Based on them, the holding costs and service level are calculated.

The Excel model considers the calculation of the next values every period:

a) Demand
b) Initial on-hand inventory
c) In-process inventory ready to be final product
d) On-hand inventory after production is released
e) Initial back-orders
f) On-hand inventory after satisfying back-orders
g) Back-orders after the previous step
h) Delivery to customer due back–ordered demand
i) Final back-order (after final demand was attended)
j) Final on-hand inventory
k) Final inventory level
l) Final work in process
m) Finish goods holding costs
n) Work in process holding costs

o) Customer service level

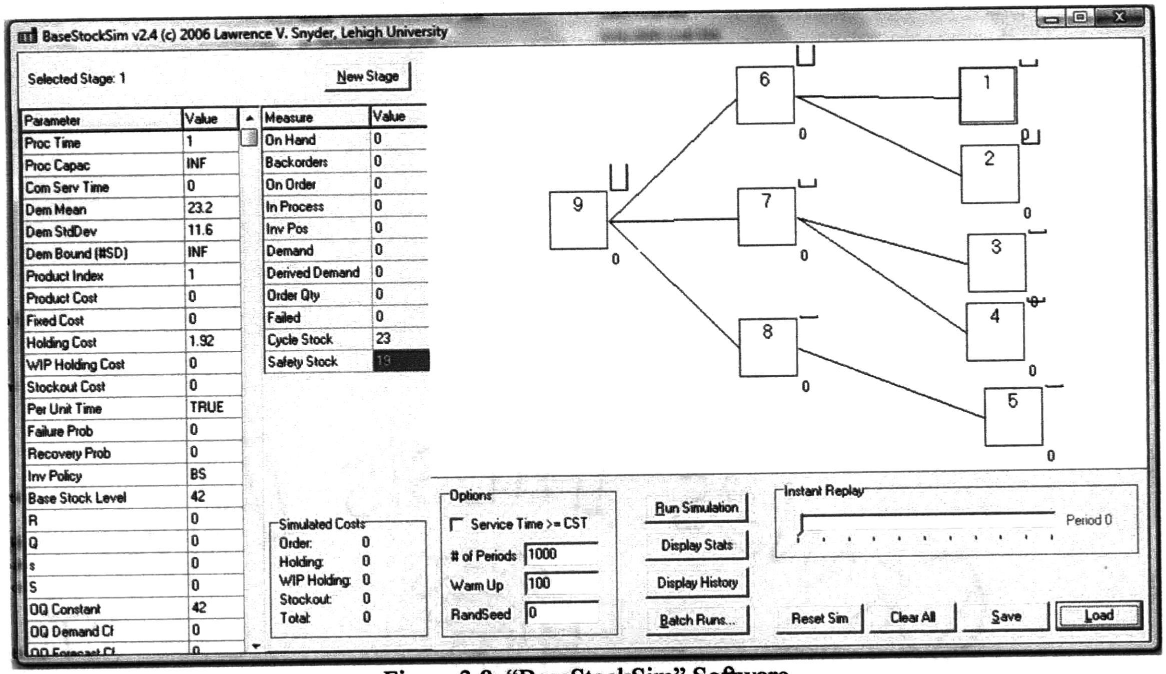
Finally, a Visual Basic routine was constructed to run the system with different inventory strategies. The number of inventory allocations run for every scenario ranges from 1,000 to 1,352. Then, each one of these particular inventory allocation strategies was run 1,000 periods of time. Additional detail about the model and several figures are included in Appendix A.

3.3.4 Model Verification and Validation

The simulation model was verified using other simulation software: "BaseStockSim" version 2.4. This is a model developed by Snyder (2006) and it is a multi-purpose base-stock simulation model. It allows the user to simulate different base-stock policies and to vary system characteristics.

A multi-echelon system equivalent to the one built in Excel was created and run to compare results. Figure 3.8 shows a screen view of the "BaseStockSim" software with this model. In spite of the differences in the random demand numbers, the results were very close.

The Excel simulation model cannot be validated with real Ternium data because the results involve costs and service level of inventory policies not tested by the company. However, the logic of the model was shown to Ternium's managers and they found it to be reasonable.



BaseStockSim v2.4 (c) 2006 Lawrence V. Snyder, Lehigh University

Selected Stage: 1

Parameter	Value
Proc Time	1
Proc Capac	INF
Com Serv Time	0
Dem Mean	23.2
Dem StdDev	11.6
Dem Bound (#SD)	INF
Product Index	1
Product Cost	0
Fixed Cost	0
Holding Cost	1.92
WIP Holding Cost	0
Stockout Cost	0
Per Unit Time	TRUE
Failure Prob	0
Recovery Prob	0
Inv Policy	BS
Base Stock Level	42
R	0
Q	0
s	0
S	0
OQ Constant	42
OQ Demand Cf	0
OQ Forecast Cf	0

Measure	Value
On Hand	0
Backorders	0
On Order	0
In Process	0
Inv Pos	0
Demand	0
Derived Demand	0
Order Qty	0
Failed	0
Cycle Stock	23
Safety Stock	19

Simulated Costs

Order:	0
Holding:	0
WIP Holding:	0
Stockout:	0
Total:	0

Options

☐ Service Time >= CST

\# of Periods: 1000

Warm Up: 100

RandSeed: 0

Instant Replay

Period 0

Figure 3.8: "BaseStockSim" Software

4 Results and Discussion

The previous chapter described the methods that we use to answer the two main questions of this thesis: where should Ternium allocate safety stock, and what method should be use to solve this problem. As we discussed, there is a conflict between Ternium's needs of decreasing safety stock (and subsequently holding costs) and the customers' needs of increasing service level and shortening service times. In addition, distribution multi-echelon systems do not have an analytical closed-form solution. That makes the choice of the method to recalculate the safety stocks when the parameters or assumptions vary non-trivial. In this chapter, we present and discuss the results of the methodology presented in Chapter 3.

For the first question, where to allocate safety stock, we developed the following sections:

- Input data & scenarios run: we present the demand data used for the calculations and the set of runs that will be tested (Section 4.1).
- Inventory strategy analysis: we depict and discuss the best inventory strategies (Section 4.2).
- Sensitivity Analysis: we explore how the inventory strategies changes for different values of service level and bounded demand. Additionally we analyze on-hand inventory behavior (Section 4.3).

For the second question, what calculation method use, we present the following sections:

- Alternative models' safety stock calculation: we calculate for the alternative models the needed SS and k-values (Section 4.4).
- Alternative models inventory strategy simulation and data comparison: the simulated results are compared against the service level-holding cost efficient frontier created and defined in Section 4.3 (Section 4.5).

Finally, the confidence intervals of the simulations were analyzed. Since they are not used in the result analysis and conclusions, those results will be included as Appendix B.

4.1 Input Data and Scenarios Run

In this section we present four topics needed to understand the results: the characteristics of Ternium's demand data (Section 4.1.1), the holding cost calculation (Section 4.1.2), the set of runs used (Section 4.1.3), and finally the analysis made to restrict the range of k-values. We call k-values the set of inventory factors used at each echelon to determine the safety stocks in the simulation model (equation 4.1 for the calculation of k, or k_{sim}).

With these topics developed, we can concentrate in Sections 4.2 and 4.3 on the allocation problem's results.

4.1.1 Demand Considerations

Ternium's demand patterns change from customer to customer. The company receives forecasted demand information from the customer, which is used for production planning. In general, Ternium also works with each customer to bound the demand; they develop an agreement on the percentage of demand variation to support on top of the forecasted quantity. At the moment, forecasted customer data is not available in Ternium's systems; only the customer final orders and dispatches can be viewed. So, we face the effect called "censored data", because the customer forecast used to generate the product order cannot be observed.

Several families of items' demand were analyzed trying to fit a single probabilistic distribution demand. The results were unsatisfactory because no distribution consistently makes a good fit for most of them.

Given that we have limited information about the demand distribution, the seasonality and the product life cycle, we decide to use the following inputs for performing the basic tests in this thesis (and the assumptions were discussed and validated by Ternium):

- Real typical multi-echelon family model configuration
- Real average demand of one item's family
- Real lead time and service time
- Calculated holding costs per period (see the following section, 4.1.2)
- Assumed independent, normally-distributed demand
- Assumed coefficient of variation equal to 0.5. (standard deviation equal to half of the average demand)

This coefficient of variance represents Ternium's variance agreement with customers sufficiently (we will discuss this more in Section 4.3.2) and allows us run normally-distributed demand models. Table 4.1 shows the demand data used as a base for the model:

Table 4.1: Selected Weekly Demand Data Case (in tons)

			Weekly Demand
Echelon 3 (M1)	Echelon 2 (M2)	Echelon 1 (FP)	**μ [t]**
CA0102501969		PA0252500549	**2.324**
		PA0252500552	**5.147**
	PA0102500333		**7.471**
		PA0252500550	**0.649**
		PA0252500553	**1.401**
	PA0102500334		**2.051**
		PA0252500628	**0.210**
	PP0102500035		**0.210**
			9.732

This family of products has 5 final products (FP), 3 intermediate products (M2) and 1 initial product (M1). Service Time (ST) is 0 weeks, LTs (or production times) are 1, 2 and 3 weeks for echelons 1, 2 and 3 respectively, as explained in Chapter 1. Ternium's item codes in columns 1 to 3 are included as a reference.

4.1.2 Holding Cost Calculation

Holding cost is the cost of carrying one unit of material in inventory for a specific period of time. It considers the combination of capital costs (or financial costs), handling costs and obsolescence cost, among others (Chopra and Meindel, 2007).

Ternium's managers do not calculate or consider holding cost values when making supply chain decisions; they try to minimize total volume of work in process (WIP) and finished goods (FG) while satisfying a customer's required SL and ST. In this thesis, holding costs are calculated considering the cost of capital, or financial cost, and the obsolescence cost. In the case of the obsolescence cost, it is related to the salvage value of the product at the end of a defined period of time. Therefore, the obsolescence, and related salvage value cost, involves more complexity in this application than the financial cost.

Salvage value is applied to any material that reaches the "Time to Salvage" in a given echelon (it ranges from 6 to 18 months). At that time, it is considered more profitable to sell the material at the salvage value (or apply it towards other orders with low yield) than keep it for the standard use. Consequently, this time and accounting process applies to only part of the total inventory for a given FP. In this analysis, we calculate holding costs by splitting this cost among all materials and applying it from the first period of time. For example, if the material value decreases 50% in 10 months, we charge an equivalent per-period (monthly) salvage holding cost of 5%. Because there is not enough information related to this topic in Ternium, we develop three cost scenarios for the costs at each of the three echelons:

- Low, High, High costs (L,H,H costs)
- Low, Low, High costs (L,L,H costs)
- Low, Low, Low costs (L,L,L costs)

The terms High or Low refers to the existence (High) or not (Low) of echelon's salvage value at each level. If it is not considered, only financial costs are included. Finally, the first of the three terms refers to the echelon 3 (farther from the customer) and the last to echelon 1 (closest to the customer). For example, a L,H,H cost scenario represents financial HC at echelon 3 and salvage and financial HC at echelon 1 and 2. We believe that scenario L, H, H is closest to Ternium's case, but all scenarios considered and tested to understand their impact. Table 4.2 shows these calculations for the three scenarios:

Table 4.2: Holding Cost Calculation

Base holding cost scenario: Low, High, High (L,H,H)

						Monthly Cost		
Echelon		F. Cost annual	Unit Cost $/tn	Time to Salvage months	Salvage	F. Cost $/tn/w	Salv. Cost $/tn/w	Total $/tn/w
3	MA2	10%	700	18	50%	1.3	4.9	6.2
2	MA1	10%	800	9	50%	1.5	11.1	12.6
1	FG	10%	850	6	50%	1.6	17.7	19.3

Intermediate holding cost scenario: Low, Low, High (L, L, H)

						Monthly Cost		
Echelon		F. Cost annual	Unit Cost $/tn	Time to Salvage months	Salvage	F. Cost $/tn/w	Salv. Cost $/tn/w	Total $/tn/w
3	MA2	10%	700	∞	50%	1.3	0.0	1.3
2	MA1	10%	800	∞	50%	1.5	0.0	1.5
1	FG	10%	850	6	50%	1.6	17.7	19.3

Minimum holding cost scenario: Low, Low, Low (L, L, L)

						Monthly Cost		
Echelon		F. Cost annual	Unit Cost $/tn	Time to Salvage months	Salvage	F. Cost $/tn/w	Salv. Cost $/tn/w	Total $/tn/w
3	MA2	10%	700	∞	50%	1.3	0.0	1.3
2	MA1	10%	800	∞	50%	1.5	0.0	1.5
1	FG	10%	850	∞	50%	1.6	0.0	1.6

The holding cost included in the "Total" column (financial plus salvage HC values) is the one used in the Excel simulation model, Graves-Willems model and the BaseStockSim software. When Time to salvage value is infinite (∞) that means that salvage value is not considered and total costs only include financial cost.

4.1.3 Simulations Run

Table 4.3 shows the tests performed to determine the best inventory strategies and do the sensitivity analysis:

Table 4.3: Simulation Runs

Objective	Run Code	k Ranges	Cost scenario	Demand
Find set of useful k_{sim}	1.1	k_{sim} from [0 – 10]^3, steps of 1	L,H,H	Unbounded
Base strategy	1.3.1	k_{sim} from [1.6 – 4] x [0 – 4]^2, steps of 1/3	L,H,H	Unbounded
Cost Sensitivity Analysis	2.3.1		L,L,L	Unbounded
Cost Sensitivity Analysis	2.3.2		L,L,H	Unbounded
Bounded Demand Sensitivity Analysis	2.3.4		L,H,H	50% bound
Bounded Demand Sensitivity Analysis	2.3.5		L,H,H	100% bound

The first column, "Objective", describes the purpose of the run. The second column, "Run Code" shows the run's reference code used in the rest of the document. The third column, "k Ranges", shows how k-values are varied in each simulation. Recall that k is the service level factor used to calculate the actual safety-stock carried at a given echelon. For example, "k_{sim} [0-10]^3, step 1" means that k_{sim} at echelons 1, 2 and 3 will be simulated for all the combinations from 0 to 10 with steps of 1. This generates 1,000 scenarios for this run (10 x 10 x 10). The logic for selected the range of the k-values is explained in Section 4.1.4. The forth column, "Cost scenario" shows the cost scenario used. Finally, the fifth columns, “Bounded demand”, shows the percentage of restriction apply to the demand with respect to its mean. We discuss the meaning of bounded demand in Section 4.3.

The two primary outputs of these set of runs, for each inventory strategy, are the average safety stock HC (per period) and the average service level. Additionally, average on-hand inventory (OH) is calculated.

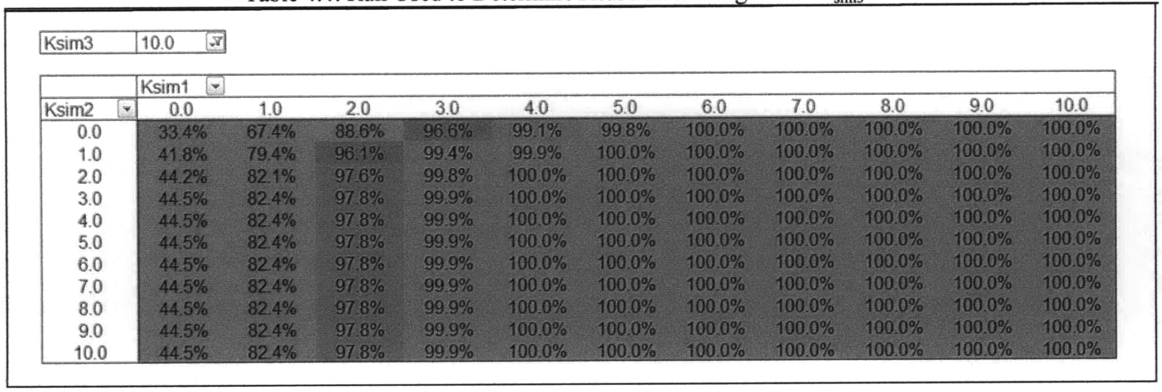
Run code scenario 1.1 (used to restrict the range of k_{sim} parameters simulated) is run with the closest cost-scenario to Ternium’s situation. If the results any of the runs for the other cost scenarios show that the k-ranges should be revised, we planned to do so. As we later show, it was not necessary to change the k-range after the initial selection from run code 1.1.

4.1.4 k-values Restriction

The range of k-values determines the number of possible inventory scenarios run for each cost or bounded demand situation. For each set of k-values (for example “1,1,1”) 1,000 weeks are run. Therefore, it takes a significant amount of time to execute each simulation run. For example, for run code 1.1, we are executing one million (1,000 x 1,000) periods. For that reason, we analyze the results of the extreme k-values, and based on those results we restrict the k-values to a more narrow range where the best solution is likely to be found. After that we can decrease the incremental steps used and refine the solutions. The k-value step used in run 1.1 is 1.

The following two tables show part of the SL's results from run code 1.1 which are used to narrow the k-values scope. For example, Table 4.4 shows the resulting service level when the k_{sim} at echelon 3 (k_{sim3}) is set equal to 10 for all the possible combinations of ksim at echelon 1 and 2. For this high value of k_{sim3}, k_{sim} at echelon 1 must be greater than 1 in order to achieve the minimum service level. Therefore, the runs performed in the following sections use a minimum k_{sim} at echelon 1 equal to 1.66.

Table 4.4: Run Used to Determine Reasonable Ranges with $k_{sim3} = 10$

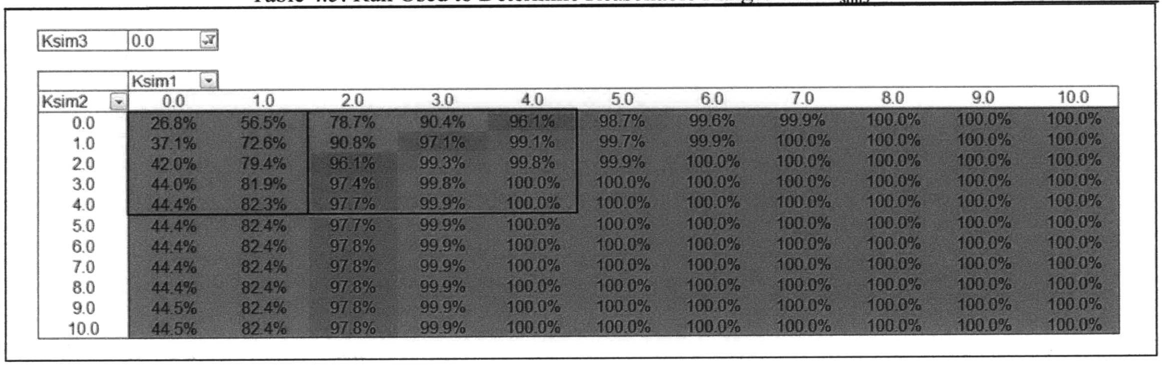


Ksim3 | 10.0

	Ksim1										
Ksim2	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
0.0	33.4%	67.4%	88.6%	96.6%	99.1%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%
1.0	41.8%	79.4%	96.1%	99.4%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
2.0	44.2%	82.1%	97.6%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
3.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
4.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
5.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
6.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
7.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
8.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
9.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
10.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Next, Table 4.5 shows the same data for $k_{sim3} = 0$. In this case, we can see that even with the worst-case inventory scenario for echelon 3 (no inventory held at all), the desired SL (greater than 95%) are reached with k_{sim} of 4.0 at echelons 1 and 2:

Table 4.5: Run Used to Determine Reasonable Ranges with $k_{sim3} = 0$



Ksim3 | 0.0

	Ksim1										
Ksim2	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
0.0	26.8%	56.5%	78.7%	90.4%	96.1%	98.7%	99.6%	99.9%	100.0%	100.0%	100.0%
1.0	37.1%	72.6%	90.8%	97.1%	99.1%	99.7%	99.9%	100.0%	100.0%	100.0%	100.0%
2.0	42.0%	79.4%	96.1%	99.3%	99.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%
3.0	44.0%	81.9%	97.4%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
4.0	44.4%	82.3%	97.7%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
5.0	44.4%	82.4%	97.7%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
6.0	44.4%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
7.0	44.4%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
8.0	44.4%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
9.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
10.0	44.5%	82.4%	97.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Based on these outputs, the simulations used in the next sections will be calculated with k_{sim} values ranging [1.6 to 4.0] for echelon 1 and [0.0 to 4.0] for echelon 2 and 3. With this range of k-values and steps of 1/3, we will simulate 1352 inventory allocation scenarios (8 x 13 x 13) and every run will involved 1,352,000 individual period's calculations.

4.2 Inventory Strategy Analysis

Table 4.6 shows results from runs codes 1.3.1, 2.3.1 and 2.3.2. They use unbounded demand and the three cost scenarios. The complete set of results is analyzed in Section 4.3; in this section we focus on the cheapest and closest results to 95% Ternium's service level requirement. The best inventory strategies (minimum holding cost with sufficient SL) are highlighted:

Table 4.6: Inventory Strategies for the Three Cost Scenarios

	L, L, L costs					**L, L, H costs**					**L, H, H costs**				
	k_{sim}			HC	SL	k_{sim}			HC	SL	k_{sim}			HC	SL
	3	2	1	$/w		3	2	1	$/w		3	2	1	$/w	
k_{sim} Values	1.0	0.0	2.0	23	88.8%	1.3	1.3	1.7	176	94.4%	1.3	0.3	2.0	263	93.7%
	0.3	0.3	2.3	24	91.5%	1.0	1.7	1.7	178	94.6%	1.0	0.7	2.0	264	94.5%
	0.3	0.7	2.3	26	93.8%	1.3	1.7	1.7	181	94.9%	**1.0**	**0.3**	**2.3**	**270**	**95.0%**
	0.7	**0.3**	**2.7**	**28**	**95.4%**	**1.0**	**2.0**	**1.7**	**182**	**95.1%**	1.3	0.7	2.0	276	95.1%
	0.0	1.0	2.7	29	95.6%	1.3	2.0	1.7	184	95.3%	0.7	0.7	2.3	281	95.4%
Average Strategy	0.5	0.5	2.4			1.2	1.7	1.7			1.1	0.5	2.1		

We analyze the inventory strategies for allocating the SS, and the relation of it to holding cost (HC) and service level (SL). To better understand the results, we discuss one of the inventory strategies here. Consider the cost scenario L,H,H: the first inventory strategy that reaches 95% SL has k-values of "1.0, 0.3, 2.3". That means that the SS at every echelon can be calculated as follow:

$$SS_1 = k_1 \times \sqrt{LT_1} \times \sigma_1 = 1.0 \times \sqrt{3} \times \sigma_1 \qquad \text{(Eq. 4.1)}$$

$$SS_2 = k_2 \times \sqrt{LT_2} \times \sigma_2 = 0.3 \times \sqrt{2} \times \sigma_2 \qquad \text{(Eq. 4.2)}$$

$$SS_3 = k_3 \times \sqrt{LT_3} \times \sigma_3 = 2.3 \times \sqrt{1} \times \sigma_3 \qquad \text{(Eq. 4.3)}$$

Since LT_i (lead times at echelon i) and σ_i (demand standard deviation at the echelon-facility i) are constant in all the inventory strategies and cost scenarios, higher k-values represent more SS inventory in the echelon and lower k-values, less SS.

For example in the same cost scenario, inventory strategy "1.3, 0.3, 2.0" carries less inventory in echelon 1 and more in echelon 3 than the previous analyzed inventory strategy, "1.0, 0.3, 2.3". Additionally, it provides a lower service level (93.7% vs. 95%) and lower HC ($263 vs $270 per week). This scenario is cheaper than the first analyzed. This HC reduction is achieved by allocating more inventories in a cheaper HC echelon and less in a more expensive one (HC for echelon 3 is 6.2 $/week/t and for echelon 1 is 19.3 $/week/t).

With these concepts understood, we can compare the average strategies calculated for each cost strategy shown in the last row of the Table 4.6. It was calculated as the average of the k-values of the displayed inventories strategies, for each echelon and cost scenario. We discuss some observations from these values below:

First, echelon 1 needs at least a k-value of 1.7 (1 ⅔) to reach 95% SL, regardless of the cost scenario used (depicted in Section 4.4) and no matter how high echelon 2 or 3 set their inventories. This can be explained using single-echelon inventory theory; the safety stock needed to guarantee 95% SL, 0 weeks of ST with a 1-week last-echelon LT must have a "k" safety stock parameter 1.65 (Section 2.1 describes single-echelon model in detail).

Second, optimal inventory allocation changes when HC changes. Consider as the initial cost scenario L, L, L. In this case inventory is positioned close to the customer, in echelon 1 ($k_{sim1} = 2.4$) and SS in echelons 2 and 3 have lower values. Echelon 1 is almost as cheap as the others but has a "time advantage" versus echelons 2 and 3 because of its closeness to the customer. When the HC of echelon 3 becomes relatively less expensive than echelon 1 and 3 (L, H, H), it holds more inventory in place of echelon 1 (the strategy changes from "0.5, 0.5, 2.4" to "1.1, 0.5, 2.1"). Finally, when echelon 2 becomes relatively cheaper than echelon 1 and close in cost to echelon 3, it holds more material in place of echelon 1 (the strategy changes from "1.1, 0.5, 2.1" to "1.2, 1.7, 1.7"). Therefore, there is a trade-off between cost and SS position. With relatively equal cost, SS is located closest to the customer. When the HC values of the echelon(s) close to the customer increase the SS moves upstream.

The extreme solution (all the SS close to the customer and 0 SS in echelons 1 and 2), which reaches an SL of 95% with k_{sim3} values about 4, is too expensive (hence it is not shown in the tables). That means that even if HC are practically equal (L,L,L cost scenario), allocating inventories in just one echelon is a bad decision.

4.3 Sensitivity Analysis

Ternium may wish to analyze its data with further detail, or it may take different approaches for some of the assumptions made, or input data may vary over time. For these reasons, it is important to understand how the decision variables behave when the input parameters change.

The following three sections describe this topic:

- HC-SL sensitivity analysis: efficient frontiers (Section 4.3.1).
- HC-SL efficient frontiers for different levels of bounded demand (Section 4.3.2).
- On Hand (OH)-SL curve (Section 4.3.3).

4.3.1 HC-SL Sensitivity Analysis: Efficient Frontiers

In this section, we analyze the results of runs 1.3.1, 2.3.1 and 2.3.2, the same as in Section 4.2, but here we take in consideration the complete set of points of the runs (1352 points per cost scenario).

To facilitate the analysis of the SL-HC trade off, we introduce the concept of "efficient frontier" (Bertsimas and Freund, 2004). The efficient frontier (EF) is a curve used by financial economist to show the best rate of return for each acceptable rate of risk, for a set of investment portfolios. For each rate of return there are several portfolios with particular risks. The one with the lowest risk is has the rate of return-risk point used in the efficient frontier; the others portfolios are confined in the space below this curve. In our case, the inventory strategy is equivalent to the financial portfolio; the service level is equivalent to the rate of return and the HC to the level of risk. Therefore we define the efficient frontier for our system as the lowest-cost strategy for a given service level.

Figure 4.1 shows the run code 1.3.1, with the cost strategy L,H,H . The blue dots represent the solutions for each one of the inventory strategies run (1352). The red curve represents the efficient frontier of these simulations. The black marks depict the analytical strategies, which will be discussed in the following sections (4.4 and 4.5).

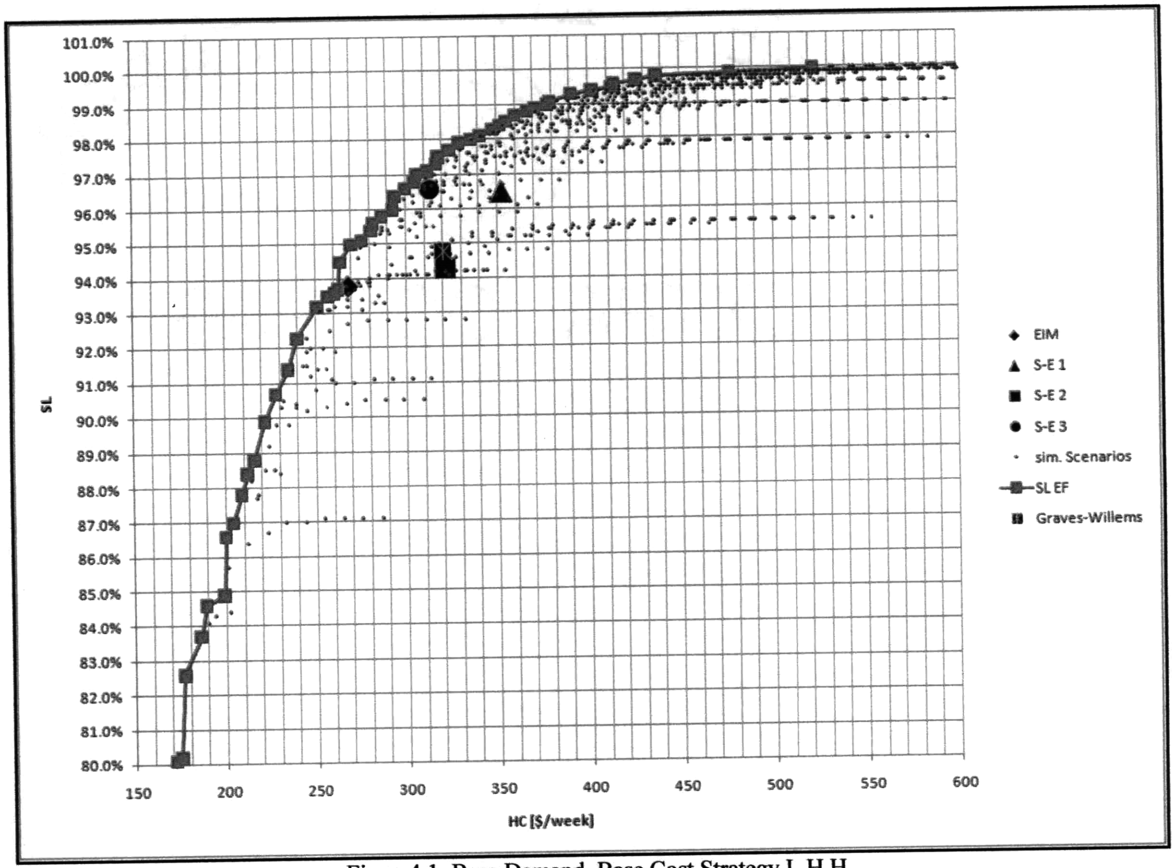


Figure4.1: Base Demand, Base Cost Strategy L,H,H

For a given SL range (for example 95 to 96%) HC varies from $260 to more than $550 per week. Similarly, for the same HC, for example about $280 per week, SL ranges from 87% to 96%. That means that choosing the right inventory strategy makes an important difference in terms of HC or SL.

Moreover, the slope of the efficient frontier is interesting. SL increases with a steep slope in the first part of the curve. Consequently, low increments in HC can generate high increments in SL. Next, when 95% SL is reached, the curve has a relatively smaller slope, and it is relatively flat when the service level reaches 99%. As a result, SL's small increases produce a lot of HC increase in the higher SL part of the curve, even using the right safety stock strategy.

Figures 4.2 and 4.3 show the same kind of figure for the other two cost strategies discussed. The run codes, from Table 4.3, are 2.3.1 and 2.3.2

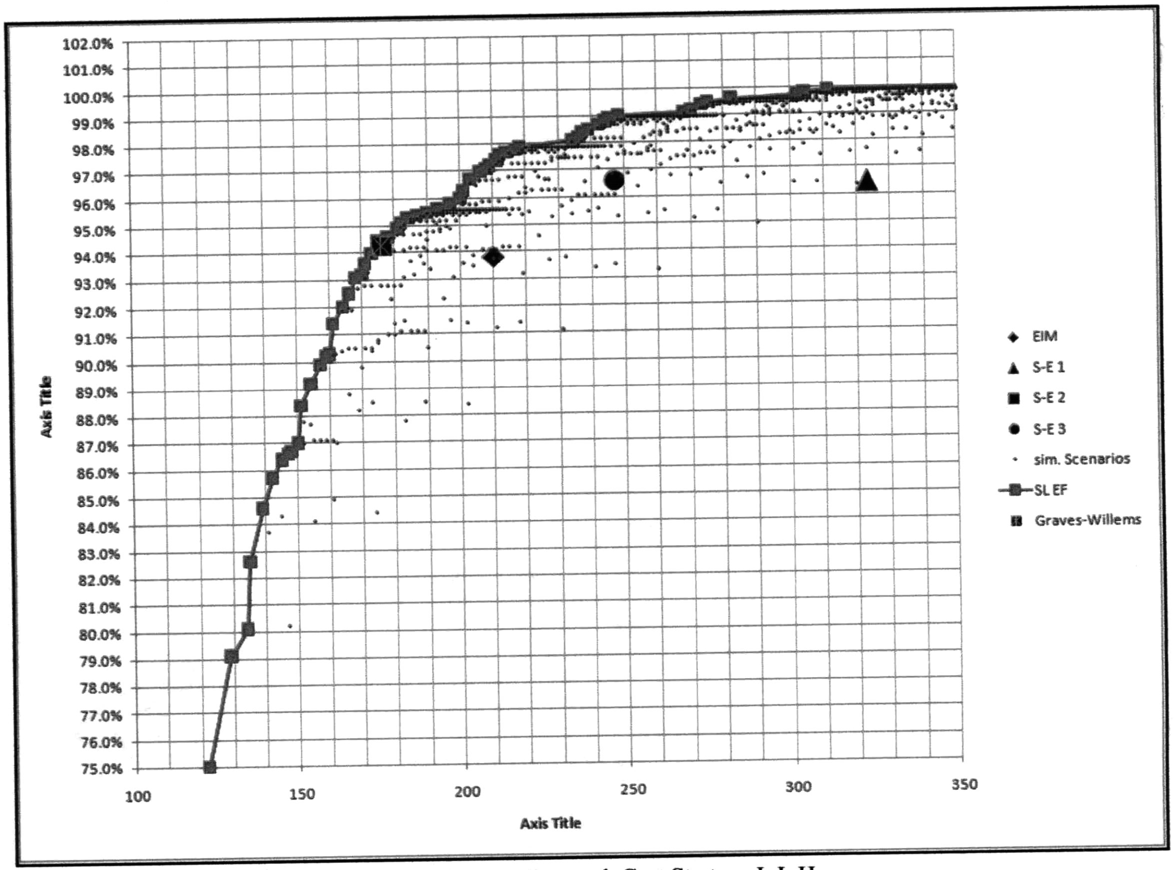


Figure 4.2: Base Demand, Cost Strategy L,L,H

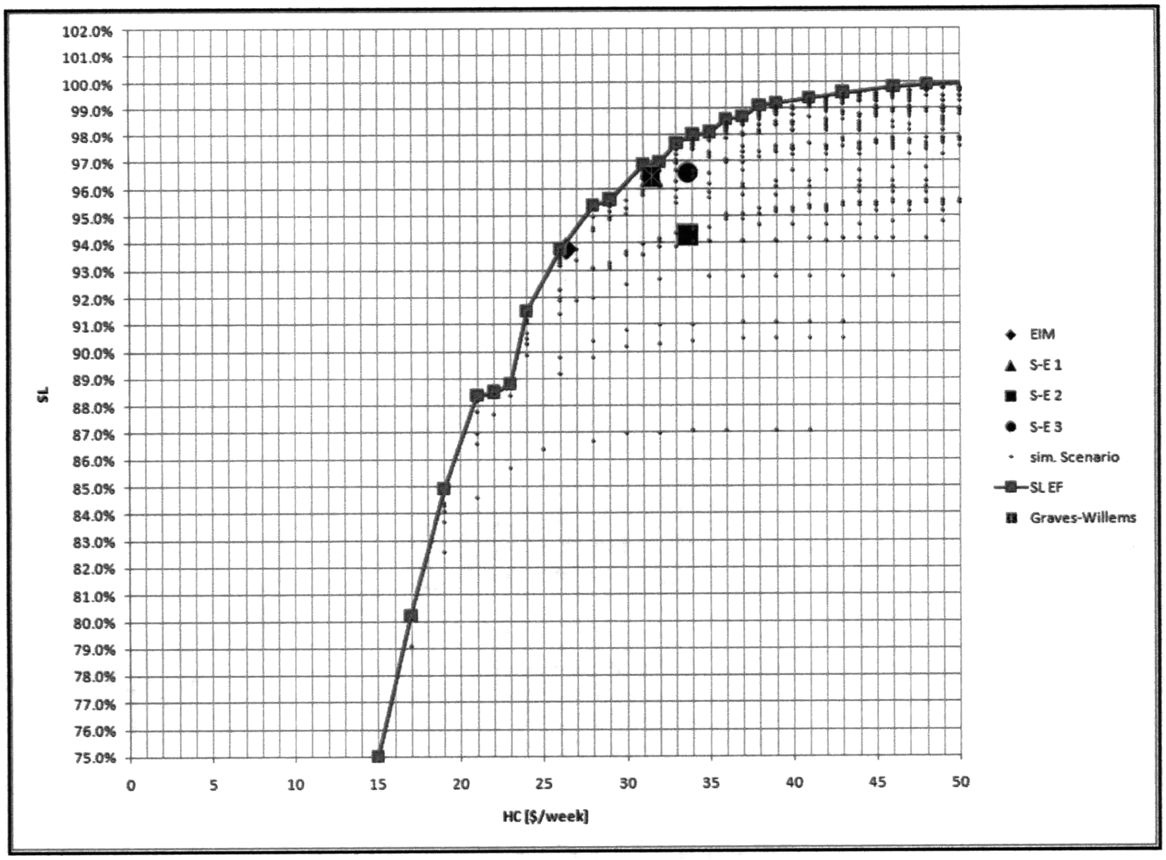


Figure 4.3: Base Demand, Cost Strategy L,L,L

Insights from these Figures are similar to those found for Figure 4.1. While the HC values are different, the behaviors of the efficient frontiers are similar. However, the inventory strategies to reach equivalent SL are very different, as we discussed in Section 4.2.

4.3.2 Bounded Demand Sensitivity Analysis

We denote "bounded demand" to represent a demand that has a restriction in its maximum value that may be observed at any period of time. As was explained in the Introduction chapter, customers provide Ternium with a forecast of their demand. If a bounded demand's agreement of "x%" exists, the customer accepts that the highest value that its actual demand can takes is equal to the forecasted demand multiplied by the factor: 1 + "x%" /100. For example, in a case of bounded demand at 50% for an item with a forecast of 10 tons per week, demands can take a maximum value of the forecast plus 50%, or 15 tons per week. This practice is not employed for all the customers at Ternium. We want to study the impact of this contract clause on system performance.

Figure 4.4 shows the efficient frontier for three scenarios of restricted demand: unbounded, bounded at 50% and at 100% of the mean demand. These scenarios correspond to the run codes 1.3.1, 2.3.4 and 2.3.5 of Table 4.3. The chart shows average SL and HC (in $ per week) for the simulations:

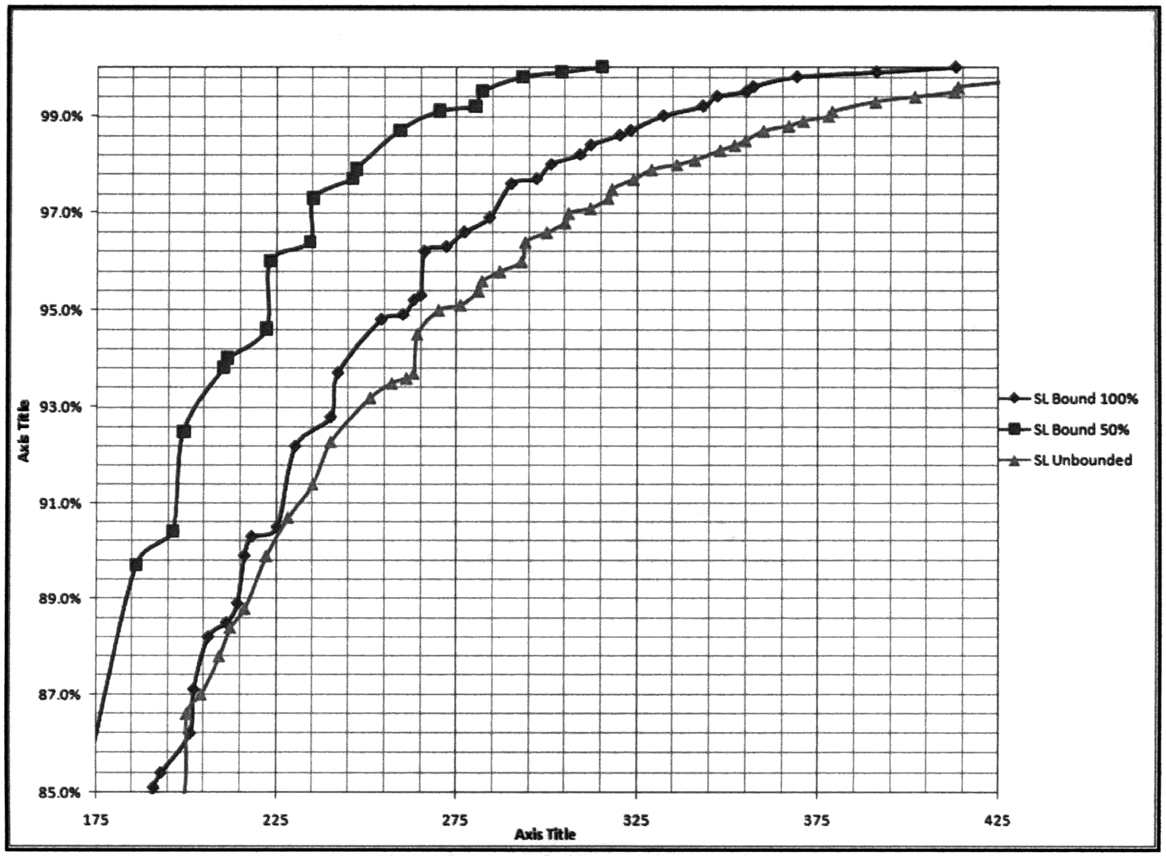


Figure 4.4: Bounded Demand Comparisons

In reality, Ternium may choose to satisfy demand even if it is greater than the bounded demand limit if they have sufficient material. However, the simulation model used does not consider the possibility of satisfying higher demand even if there is enough inventory. This avoids the potential of a decrease in SL in the following simulated weeks, which allows for a better understanding of the impact of the supply policy.

The figures shows that by restricting demand variation to 50% we can reduce HC by about 20%. Therefore, these contract characteristics can potentially be very valuable.

4.3.3 On Hand Inventory Sensitivity Analysis

Ternium's inventory planning is currently based on the control of total on-hand inventory (WIP and FG). For this reason, it is interesting to understand how on-hand inventory behaves in the most efficient inventory strategies (those that make up the efficient frontier).

We constructed a chart with the same inventory strategies of the efficient frontier found in Figure 4.1; but instead of HC the chart depicts OH inventory versus SL. The dots were joined in the same order as in the case of the EF. Figure 4.5 shows the results (cost scenario L,H,H, run code 1.3.1):

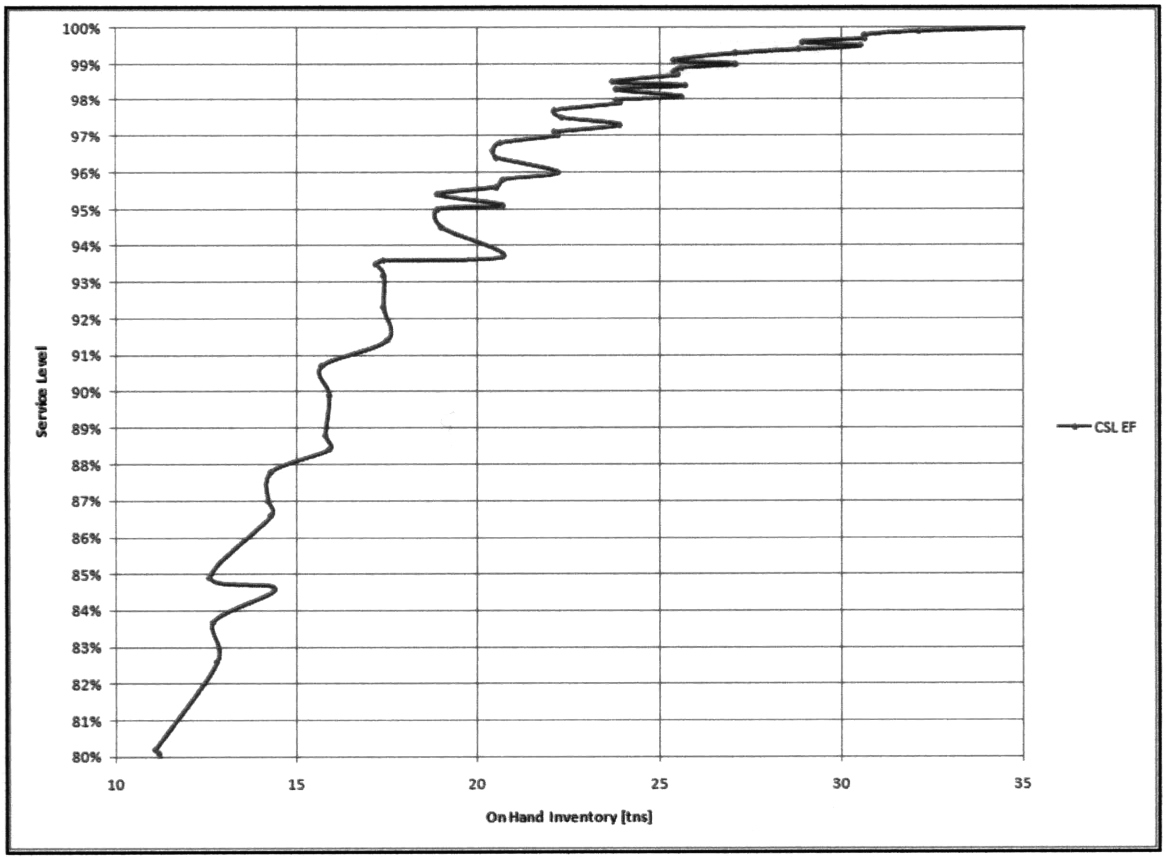


Figure 4.5: On-Hand Safety Stock Inventory vs Service Level

The curve has changed dramatically compared with HC-SL efficient frontier; it is neither smooth nor continually increasing as the curves of Figure 4.1, 4.2 or 4.3 were. The same OH level may have multiple associated SL values; see OH equal to 20, for example.

Figure 4.5 shows that a decrease in on-hand inventory may mean *either* a decrease or an increase in SL. It is the positioning of the on-hand inventory, not the total volume, that determines costs and SL.

4.4 Alternative Models' Safety Stock Parameters Calculation

In this section we show the calculated k-values for the analytical and Graves-Willems models' inventory strategies for the three different cost scenarios. This is covered in Sections 4.4.1 and 4.4.2 respectively: this data will be used in Section 4.5 to compare the simulation of these inventories strategies versus the EF.

4.4.1 Deterministic Models' Safety Stock Parameters

This section presents the safety stock outputs calculated using the analytical models described in Sections 3.3.1 and 3.3.2. The analysis includes three safety stock strategies using the single-echelon inventory models (strategies 1 to 3) and two safety stock strategies using the echelon-inventory model (strategies 95/99/99% and 99/99/99%). Figure 4.6 shows the calculations and resulting safety stock determined by these models.

Table 4.7: Analytical Models' Safety Stock Parameters

		NRL/ENRL			k_{sim}		
Model	Strategy	Echelon 3	Echelon 2	Echelon 1	Echelon 3	Echelon 2	Echelon 1
Single-Echelon	1	0	0	6	0.00	0.00	4.03
	2	0	5	1	0.00	2.60	1.64
	3	3	0	3	1.64	0.00	2.85
Echelon-Inventory	95/99/99 %	6	3	1	0.35	1.31	1.64
Echelon-Inventory	99/99/99 %	6	3	1	0.35	0.67	2.33

Safety stock is calculated using equations 3.1, 3.2 and those included in Figure 3.5. In the case of the Single-Echelon models, k_{sim} is calculated using the net replenish lead time (NRL), as explained in Section 3.3.1. For the echelon-inventory model, the echelon net replenishment lead time is used (ENRL), as discussed in Section 3.3.2. SS values are not shown in the table; it only shows k-values (k_{sim} for each echelon), since they allow for easier interpretation and are directly related to the SS. k_{sim} are derived using Eq. 4.4:

$$k_{sim} = \frac{SS_{ij}}{\sqrt{LT_i} \times \sigma_i}, \tag{Eq. 4.4}$$

where

- SS_i: Safety stock calculated in the facility j of the echelon i.
- LT_i: Lead time at echelon "i",
- σ_i : demand standard deviation,
- $i \in [1,3]$.

These k-values will be used as inputs in the simulation model.

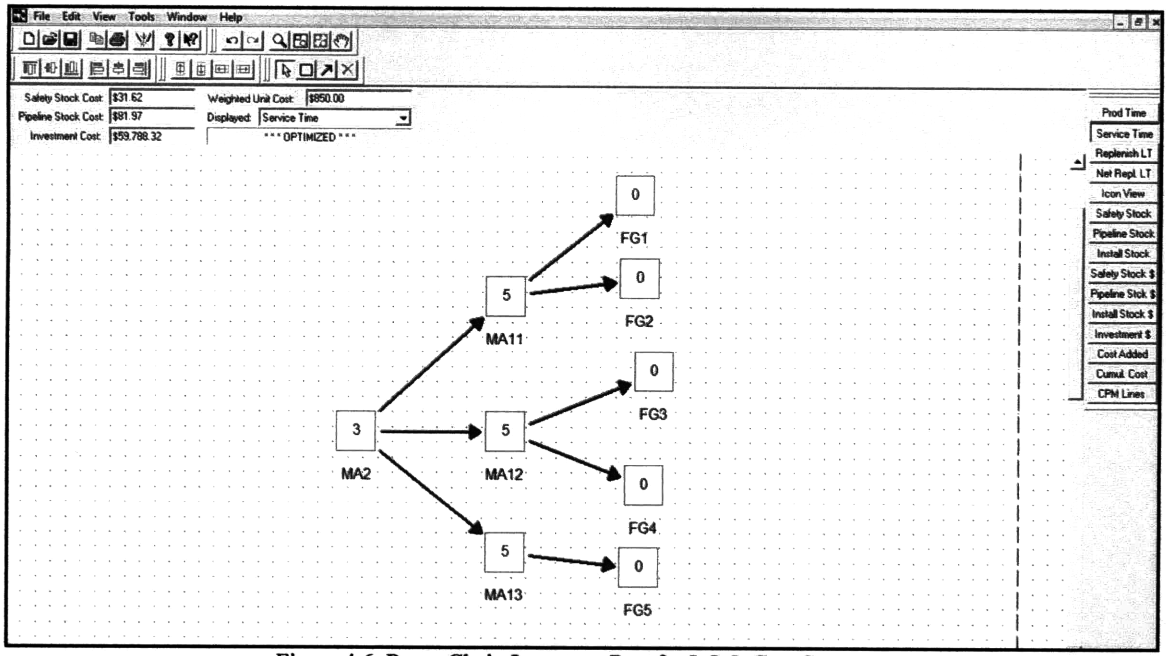
4.4.2 Graves-Willems Model's Safety Stock Parameters

The three cost scenarios were loaded and run in the PowerChain Inventory software, which applies the Graves-Willems model. When the model optimizes the system, it calculates the service time that every echelon will provide to the next one. The k_{sim} parameters are shown in Table 4.7, which were calculated using Eq. 4.4:

Table 4.8: Graves-Willems' Safety Stock Output Levels

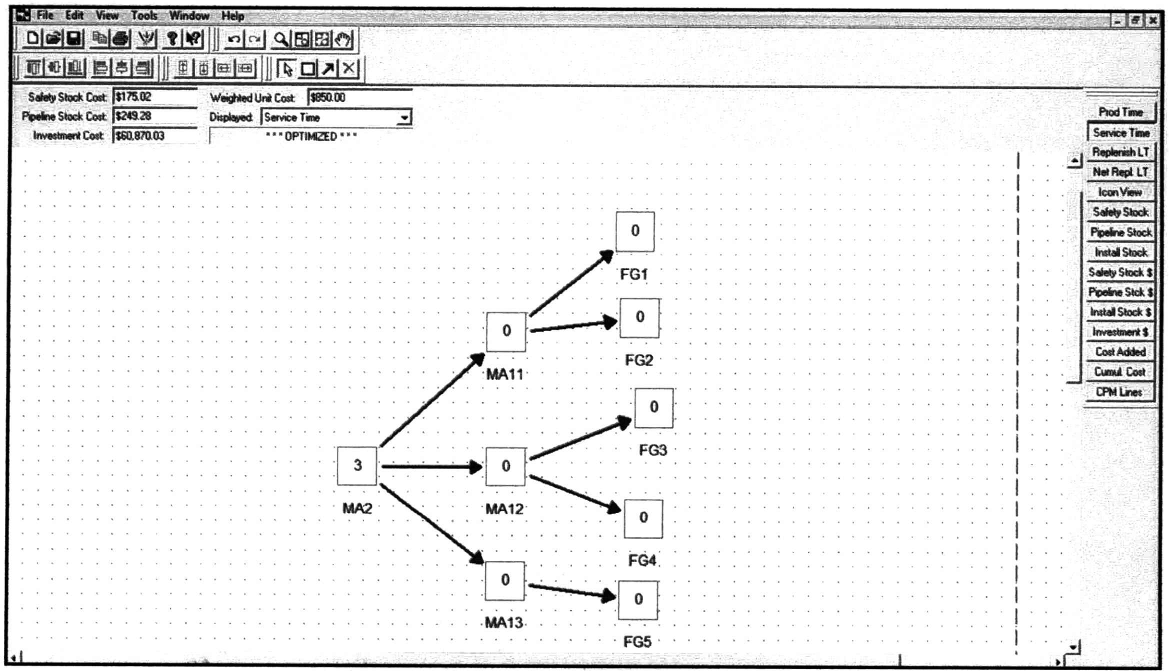
		k_{sim}		
Model	Cost scenario	Echelon 3	Echelon 2	Echelon 1
Graves-Willems	L,H,H cost	1.64	1.64	1.64
	L,L,H cost	0	2.6	1.64
	L,L,L cost	0	0	4.03

As an example, Figures 4.7 and 4.8 show runs for the cost scenarios L,L,H and L, L, L. The figures are "print screen" pictures of the software. They show, in the software work zone, a scheme of the model: five FP, three M2 and one M1 locations connected in a distribution multi-echelon model. The boxes represent the facilities (9) and the vertical arrangements the echelons. In this case, echelon 3 has one facility, echelon 2 has three facilities and echelon 1 has five facilities. Each box can show different inputs or results of the run, based on a value selected from the buttons on the right of the screen. In this case "Service Time" is selected, which is the output of the run. In the upper part of the screen, below the icon buttons, data related to per-period costs is shown.



Safety Stock Cost: $31.62
Pipeline Stock Cost: $81.97
Investment Cost: $59,788.32
Weighted Unit Cost: $850.00
Displayed: Service Time
*** OPTIMIZED ***

Figure 4.6: PowerChain Inventory Run for L,L,L Cost Strategy



Safety Stock Cost: $175.02
Pipeline Stock Cost: $249.28
Investment Cost: $60,870.03
Weighted Unit Cost: $850.00
Displayed: Service Time
*** OPTIMIZED ***

Figure 4.7: PowerChain Inventory Run for L,L,H Cost Strategy

Cost scenario L,H,H's resulting figure was included in Chapter 3 (Figure 3.6) when the logic of the model was described.

4.5 Alternative Method's Simulation and Data Comparison

The motivation for this evaluation is to try to find a calculation method robust to different cost configurations. Ternium may not choose to construct an excel simulation for every future decision, but may seek to use one of these simpler models for decision-making. Thus finding a robust method is important for two reasons: first, the analytical models applied do not vary with the cost parameters (the k parameter is determined independent of the costs), and second, Ternium's cost parameters could change or be considered differently. As a result, we must analyze the result of the models in the 3 cost scenarios before concluding which can provide precise and stable solutions.

The analytical and the Graves-Willems models' inventory strategies where simulated in the Excel model. k-values from Tables 4.7 and 4.8 were used as inputs in the simulation model for each cost scenario. Table 4.8 shows the average service level (SL), holding costs (HC) and on-hand safety stock (OH) for the run code 1.3.1 (cost scenario L,H,H):

Table 4.9: Analytical and Graves-Willems Inventory Strategies' Simulations for Run-Code 1.3.1

Model	Strategy	k_{sim}			Avr.SL	Avr. HC [$/w]
		Echelon3	Echelon2	Echelon1		
Single-Echelon	1	0.00	0.00	4.03	96.5%	352
	2	0.00	2.60	1.64	94.3%	321
	3	1.64	0.00	2.85	96.6%	313
Echelon-Inventory	95/99/99 %	0.35	1.31	1.64	91.7%	251
	99/99/99 %	0.35	0.67	2.33	93.8%	268
Graves-Willems	L,H,H cost	1.64	1.64	1.64	94.8%	320

Inventories strategies for the single-echelon model and echelon-inventory model were explained in Chapter 3. Their k-values are not affected by the cost parameters and scenarios. Table 4.9 shows that service levels range from 91.7% to 96.5% (target 95%) and that holding costs range from $251 to $352 per week. For example, SE strategy 3 looks like the cheapest and closest to 95% SL.

In order to compare the results in the three cost strategies with the simulated efficient frontier (EF), they were included as black symbols in Figures 4.1, 4.2 and 4.3 in Section 4.3.1. The figures depict that some of the alternative models' results are closest than others to the efficient frontier. For example, in cost scenario L,H,H the echelon-inventory model and the SE strategy 3 are almost on the efficient frontier, but both are far from 95%. Additionally, some strategies are consistently below 95%.

We compare the results of the alternative models versus the efficient frontier in Table 4.10. To facilitate the comparison we use the EF to make a regression function in order to predict the exact HC value that provides a 95% SL. We choose the 5 output values closest to 95% SL and fit with them a linear regression function (as shown in the charts in Figure 4.8). The extrapolated HC are depicted in Columns "SL at 95%".

Table 4.10 has 2 parts. The first 6 data rows show strategies that compound the EF and the last 5 rows the strategies from the alternatives method and their HC and SL. Both tables are separated according to the three cost strategies. The regression charts shows the dots of the EF made by the 5 strategies of the first rows and the regression function associated.

Finally the last column, "% Δ Cost", is calculated as the average percentage of extra HC between the selected method and the efficient frontier, both at 95% SL. For example, the 9.7% of average extra HC of the Graves-Willems method is calculated as:

$$\%\Delta\, HC = \left[\frac{30.2-27.7}{27.7}+\frac{182-181}{181}+\frac{322-270}{270}\right]/3 = 9.7\%$$

For these scenarios, the echelon-inventory model gives an average extra cost of 8.2%, the Graves-Willems models 9.7% and the best single-echelon strategy 15.4%. The worst scenario, the single echelon inventory strategy 1 (holding all inventory close to the customer), generates 35% extra holding costs.

Table 4.10 Simulation Comparisons and Regression Results

	Cost Strategy												
	L, L, L				L, L, H				L, H, H				% Δ HC
Model	Strategy	HC	SL	HC at 95%SL	Strategy	HC	SL	HC at 95%SL	Strategy	HC	SL	HC at 95%SL	
Simulation Efficient Frontier	1.0_0.0_2.0	23	88.8%		1.3_1.3_1.7	176	94.4%		1.7_0.3_2.0	263	93.7%		
	0.3_0.3_2.3	24	91.5%		1.0_1.7_1.7	178	94.6%		1.0_0.7_2.0	264	94.5%		
	0.3_0.7_2.3	26	93.8%		1.3_1.7_1.7	181	94.9%		1.0_0.3_2.3	270	95.0%	270	
	0.7_0.3_2.7	28	95.4%	27.7	1.0_2.0_1.7	182	95.1%	181	1.3_0.7_2.0	276	95.1%		
	0.0_1.0_2.7	29	95.6%		1.3_2.0_1.7	184	95.3%		0.7_0.7_2.3	281	95.4%		
	0.5-0.5-2.4				1.2-1.8-1.7				1.1-0.5-2.1				
Graves-Willems	0.0-0.0-4.03	31.5	96.5%	30.2	0.0-2.60-1.64	176	94.3%	182	1.64-1.64-1.64	320	94.8%	322	9.7%
EI	0.35-0.7-2.3	26.4	93.8%	27.4	0.35-0.7-2.3	210	93.8%	220	0.35-0.7-2.3	268	93.8%	280	8.2%
S-E 1	0.0-0.0-4.03	31.5	96.5%	30.2	0.0-0.0-4.03	323	96.5%	310	0.0-0.0-4.03	352	96.5%	337	35.0%
S-E 2	0.0-2.60-1.64	33.7	94.3%	34.3	0.0-2.60-1.64	176	94.3%	182	0.0-2.60-1.64	321	94.3%	328	15.4%
S-E 3	1.64-0.0-2.85	33.7	96.6%	32.3	1.64-0.0-2.85	247	96.6%	233	1.64-0.0-2.85	313	96.6%	297	18.5%

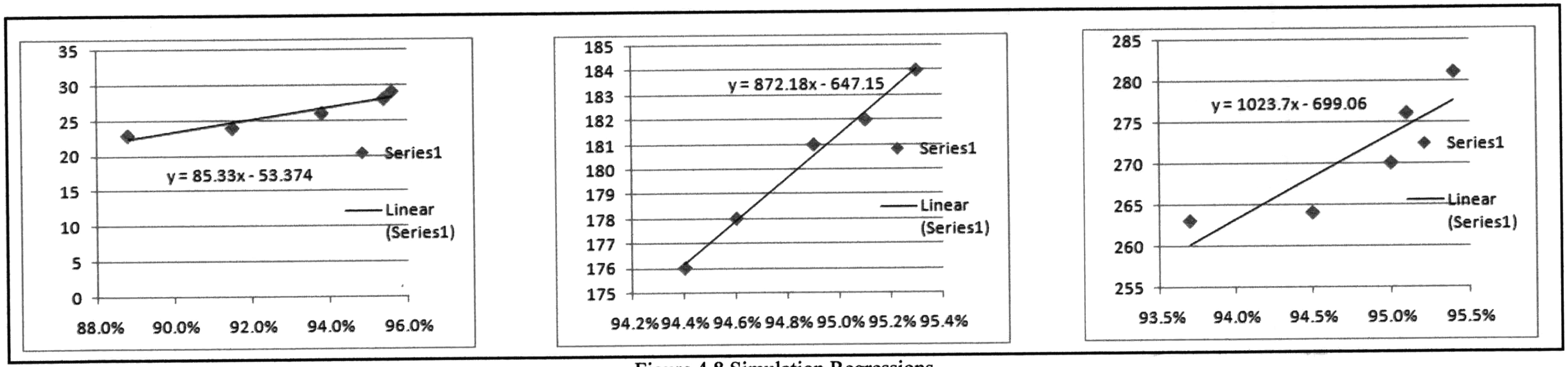


Figure 4.8 Simulation Regressions

It is important to highlight that while the echelon-inventory model produced low cost scenarios, it also generates some problems to be dealt with before the results can be applied. As explained in Section 3.2.1, a desired SL must be selected to calculate the base-stock at each echelon. When a SL of 95% for the first echelon and 99% for the second and third echelons were used to generate base-stock levels, and those levels were simulated, they only produced a 92% SL. Thus, it was necessary to increase the SL to 99% in the first echelon to even get a final simulated SL close to 94%. If a simulation model were not available, it would be difficult to detect this problem and evaluate the performance of the base-stock levels output by the echelon-inventory model.

The alternative methods generate good results, especially the Graves-Willems model and the echelon-inventory model, but simulating the exact model produces important cost savings. Thus simulation is a powerful tool to evaluate and test the impact of different inputs and performance of the system.

5 Conclusions and Recommendations

In this final chapter, we present three main topics: academic conclusions, managerial conclusions or insights, and finally, topics that can be extended or analyzed in further studies. The two first sections, academic and managerial conclusions, have two parts; each of them focused on the insights that were generated answering the two main questions of the thesis:

- Where should we allocate safety stock to satisfy service levels and minimize holding cost in Ternium's multi-echelon system?
- What method should Ternium use to solve the problem in the future?

Some of the main topics are repeated in the academic and managerial sections, but we discuss their different connotations in each one.

5.1 Academic Conclusions

5.1.1 Inventory Allocation

The calculation of the safety stock allocation can be accomplished using simulation, but results are very sensitive to cost parameters. Good results were found using simulation, as was shown in Chapter 4, but results can vary greatly with changes to cost parameters. We found the best inventory strategy for the base cost scenario (Table 4.6) but slight changes of cost cause significant movement of inventory among echelons in the best solutions. Other parameters, such the supply chain shape of the system (consider for example a serial 3-echelon system or a distribution 3-echelon system with 5 or 10 final facilities) and the demand correlation of the items, have a strong impact too. These are all parameters that exist in Ternium's system.

An in-depth characterization of the product and demand must be the first focus of these inventory problems. Based on the sensitivity of the solutions, a strong focus on characterizing demand in multi-echelon systems is important. Analysis based on average volume is a beginning, but characterizing item demand based on parameters such as the shape of the supply chain, demand correlation and salvage value behavior are more important. Additionally, the probabilistic analysis of the demand is another critical consideration of the problem.

Customer contract variables could be important in the solution. We explored the impact of a practice that Ternium performs with some of its customer: bounding the variation of the demand (above the customer's forecasted levels). As shown in Section 4.3.2, this technique proves to be extremely effective to reduce holding costs.

Focusing solely on the control of on-hand inventory levels, or cost of on-hand inventories, leads to inefficient results. This is the strategy currently used by the company to measure inventory management performance. Wide-spread metrics, such as inventory turnover, reinforces this approach. We demonstrated in Section 4.3.3 how this policy can lead to bad results.

5.1.2 Calculation Methods

Single echelon models do not perform well as a stand-alone method. Section 4.5 shows that SE strategies preformed far worse than the more thorough methods. Results were an average 15 to 35% more expensive than the simulated results, and were 6 to 26% more expensive than the other analysis methods used.

The echelon-inventory model performed well, but tended to generate lower service levels than expected. Section 4.5 showed the general results of all the alternative methods. The echelon-inventory model has costs only 8.2% over the best simulated solution, making it the lowest-cost alternative method considered. However, it was very difficult to set the SL parameters used to calculate the inventories. They were increased to 99% in all the echelons to get a simulated SL of 93.8%. If the simulation model were not available, it would be difficult to set the model to get the desired SL. Thus, results are good but need the help of other models to be fine-tuned.

The Graves-Willems model produces good results. As shown in Section 4.5, this model was 9.7% in average over the best simulated result and 1.5% over the echelon-inventory model. In addition, the service level found was always very close to 95%. Also, this method has a good characteristic that simple methods do not have: if cost parameters change, the model could be easily updated.

Simulation is extremely useful in multi-echelon problems. Simulation allows comparison of all the models, which alone would have given non-comparables "good" results (non-comparable meaning very difficult to compare in the same context and against a base method). In addition, this technique allowed for generation of the HC-EF frontiers and determination of the best solution. A useful alternative would be a model that mixed simulation with optimization.

5.2 Managerial Conclusions

5.2.1 Inventory Allocation

We presented precise results and some general ideas about where to allocate inventories. In general, we showed that if the holding cost of the first facility is similar to the other ones, most (but not all) of the material should be allocated close to the customer. On the other hand, if the holding cost of the farther facilities becomes cheaper, the inventory will move upstream. Precise values and these considerations were discussed in Section 4.2. Reducing the risk-pooling effect (through positive demand correlation or considering smaller or serial-structured supply chains) will increase the desire to allocate material close to the customer.

Keeping all the SS just in the first echelon, close to the customer, is a bad solution with respect to cost. If Ternium uses enterprise resource planning (ERP) to manage a make-to-order (MTO) process, this strategy is easy to apply. Ternium could just produce material in advance to build to the desired final-echelon inventory level, instead of managing different positions' push-pull boundaries. However, in the cost comparison conducted in Section 4.5, Table 4.8, we showed that this strategy lead to a cost increase of 35%.

Thorough understanding of input parameters is critical in solving the problem. In this thesis we made an assumption about the salvage value and how to translate it into to holding costs. True understanding of holding costs will lead to better results. It is important to consider customer information integration to improve the understanding of the product's life cycle at each echelon and minimize the risk of scrapping material.

The same concept applies to supply chain shape and item aggregation. Aggregating more or less items in the supply chain will change the safety stock allocation. Thus this is another important decision to consider.

Bounded demand strategies are good solutions. This strategy reduces costs by a significant amount (see Section 4.3.2). It is worthwhile to expand it to more customers. In the case of industrial customers, they usually face production constraints. Therefore, bounding their extreme demand could be feasible for them.

Develop indicators able to measure holding costs and avoid to total on-hand inventory as the only indicator. As was shown in Section 4.3.3, trying to optimize total system holding costs by minimizing on-hand inventory does not work. A more holistic approach must be taken. We recommend keeping the on-hand metric for day to day operations, once the safety stocks are defined, but avoiding it when designing the inventory strategy.

IT Planning systems must be prepared to support different strategies. As we explained, an ERP system created to manage MTO only will not support the different push-pull boundaries needed. If it is not desirable to modify the ERP system, other forecasting and planning models must tackle the problem.

5.2.2 *Methodology Suggested*

1. In-depth characterization of the demand and the subjacent multi-echelon system structure.
    a. Prepare the system to operate dynamically, managing the creation and elimination of items.
    b. Split demand in a useful number of categories, according to parameters related to supply chain shape, holding cost behavior, standard deviation, etc.
    c. Link to the customer to monitor demand, item's life cycle, campaigns, etc. Explore contract variables that impact this problem (bounded demand, pay-back contract, etc)
2. Use simulation or the Graves-Willems model to set the inventory to define SS strategies for the main characterized families. Put threshold signals in place to understand when to recalculate the strategies.
3. Prepare the systems to manage push-pull boundaries in different positions. If the ERP cannot handle this situation, other IT Planning systems must be developed to manage it.
4. Develop metrics. Measures to monitor that the system is performing well are critical. Employee participation and assignment of responsibilities are important too, especially to help in getting information from customers. The area primarily in charge of the relation with the customer must be part of the solution. In Ternium's case, this would be the Sales Vice President.

5.3 Further Considerations

In this section, we discuss some additional considerations that could impact the practical application of the results of this thesis. We also list some topics that could be the subject of further studies.

Production variability should not be ignored if it is significant. This thesis work was focused on safety stock and demand variation. While it is true that Ternium's production line variation is small, in the cases in where it is large, it must be considered in the model. One option is to include it as a lead time variation; another is to simply increase the lead time value.

Another important consideration is buffers. They hold most work in process, and even some finish goods. Buffers are used to decouple production lines within a facility, or are associated with scheduling rules and production campaigns. It would be interesting to understand the effort needed to improve SS (following the steps presented in Section 4.2.2) and its relation to total holding costs, including buffers. Projects based on improving buffer policies could have additional pay-off.

Set up costs were not considered. They need to be included in lines in where the impact is important. Coping with them is related to the demand characterization; low demand items could have a particular inventory policy to avoid the production of less than a minimum allowed volume.

Finally, we conclude with a list of some of the areas that could be explored using this thesis as a base:

- Include lead time variation.
- Consider set-up cost.
- Develop a model to aggregate items in families.
- Consider supply contracts oriented to optimize this process.
- Discuss the impact of customer integration.
- Develop a planning model to manage the problem integrally (item and demand family management, forecasting and planning).

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Appendix A: Simulation Model

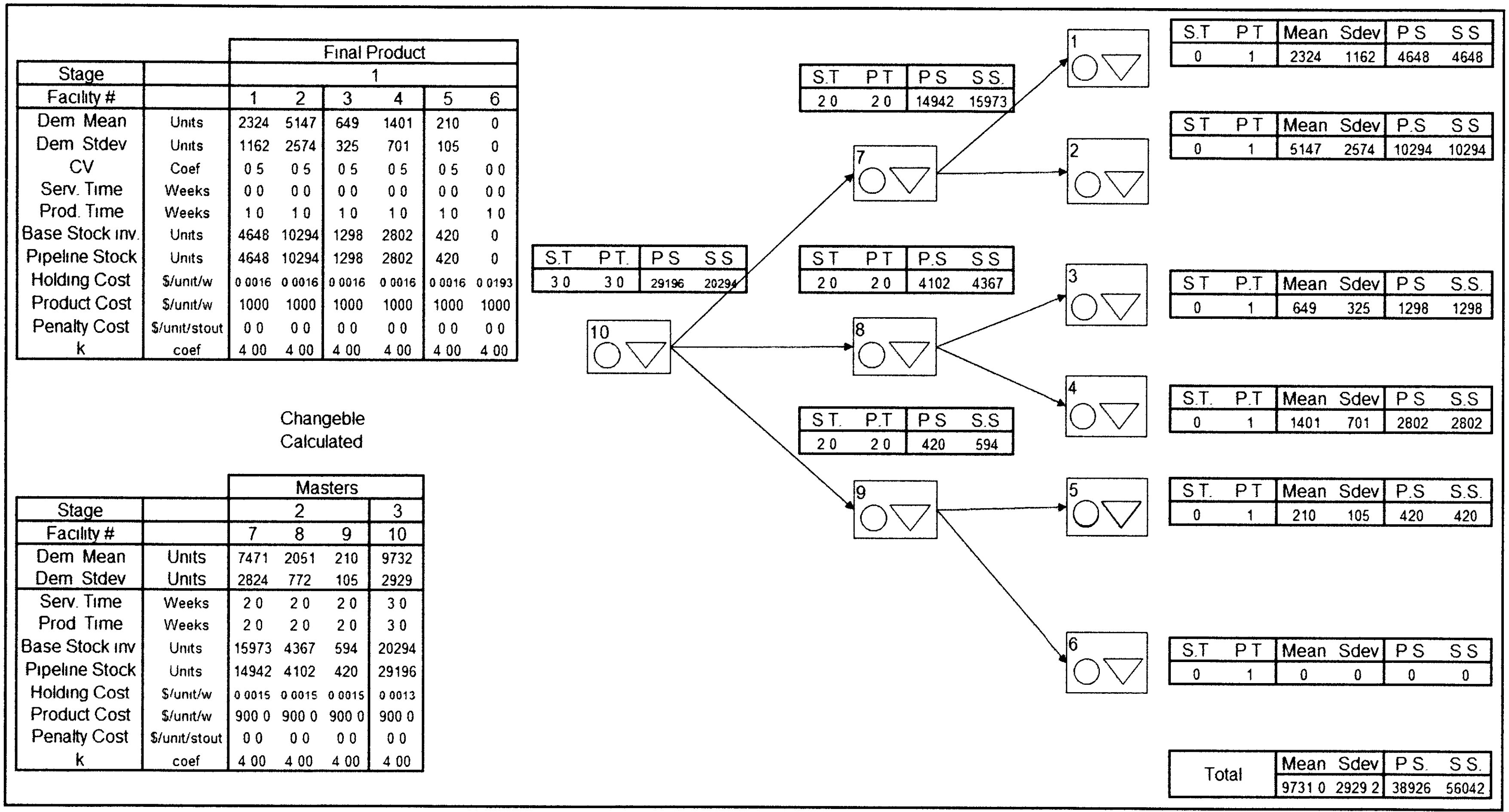
This appendix presents additional information about the Excel model constructed. While this distribution model can be simulated through ad-hoc tools, such as the cited "BaseStockSim" model, Excel was chosen as the tool to facilitate the run of a large number of allocation strategies automatically. Otherwise, the finding of the best solutions using other software would have been a trial-and-error process. This appendix does not describe all of the details of the model; the objective is to give an overview of the tool used.

Figure A.1 shows the input model data. Demand parameters, holding costs and the general shape of the models are depicted. While the model is prepared to run six final products (for added flexibility), it is used in this thesis for simulating a 5-final product multi-echelon system. Tables and graphs depict main demand data, as well as pipe-line stock (PL) and safety stock (SS).

Figure A.2 shows the calculation engine of the models. It is constructed using 204 columns which involve all the calculations needed to simulate 1 period (1 week) and keeps the information required for the next period of time. The main variables calculated are described in Section 3.3.3. We run 1000 periods of time (weeks) for each allocation strategy (1,352 strategies in the case shown). The picture corresponds to one of the cost scenarios.

Figure A.3 shows the macro generated to vary the 1,352 allocation strategies, run the engine and save the results. Each run (involving the 1,000 periods of time for the 1,352 allocation scenario) lasts about 2 hours in a computer with a 2.1 GHz microprocessor and 4 GB of memory RAM.

Finally, Figure A.4 shows the final generated table with the average holding costs (HC), on-hand inventories (OH) and service levels (SL) for each allocation strategy.



		Final Product					
Stage		1					
Facility #		1	2	3	4	5	6
Dem Mean	Units	2324	5147	649	1401	210	0
Dem Stdev	Units	1162	2574	325	701	105	0
CV	Coef	0.5	0.5	0.5	0.5	0.5	0.0
Serv. Time	Weeks	0.0	0.0	0.0	0.0	0.0	0.0
Prod. Time	Weeks	1.0	1.0	1.0	1.0	1.0	1.0
Base Stock inv.	Units	4648	10294	1298	2802	420	0
Pipeline Stock	Units	4648	10294	1298	2802	420	0
Holding Cost	$/unit/w	0.0016	0.0016	0.0016	0.0016	0.0016	0.0193
Product Cost	$/unit/w	1000	1000	1000	1000	1000	1000
Penalty Cost	$/unit/stout	0.0	0.0	0.0	0.0	0.0	0.0
k	coef	4.00	4.00	4.00	4.00	4.00	4.00

Changeble
Calculated

		Masters			
Stage		2			3
Facility #		7	8	9	10
Dem Mean	Units	7471	2051	210	9732
Dem Stdev	Units	2824	772	105	2929
Serv. Time	Weeks	2.0	2.0	2.0	3.0
Prod Time	Weeks	2.0	2.0	2.0	3.0
Base Stock inv	Units	15973	4367	594	20294
Pipeline Stock	Units	14942	4102	420	29196
Holding Cost	$/unit/w	0.0015	0.0015	0.0015	0.0013
Product Cost	$/unit/w	900.0	900.0	900.0	900.0
Penalty Cost	$/unit/stout	0.0	0.0	0.0	0.0
k	coef	4.00	4.00	4.00	4.00

S.T	P.T.	P.S	S.S
3.0	3.0	29196	20294

S.T	P.T	P.S	S.S.
2.0	2.0	14942	15973

S.T	P.T	P.S	S.S
2.0	2.0	4102	4367

S.T.	P.T	P.S	S.S
2.0	2.0	420	594

S.T	P.T	Mean	Sdev	P.S	S.S
0	1	2324	1162	4648	4648

S.T	P.T	Mean	Sdev	P.S	S.S
0	1	5147	2574	10294	10294

S.T	P.T	Mean	Sdev	P.S	S.S.
0	1	649	325	1298	1298

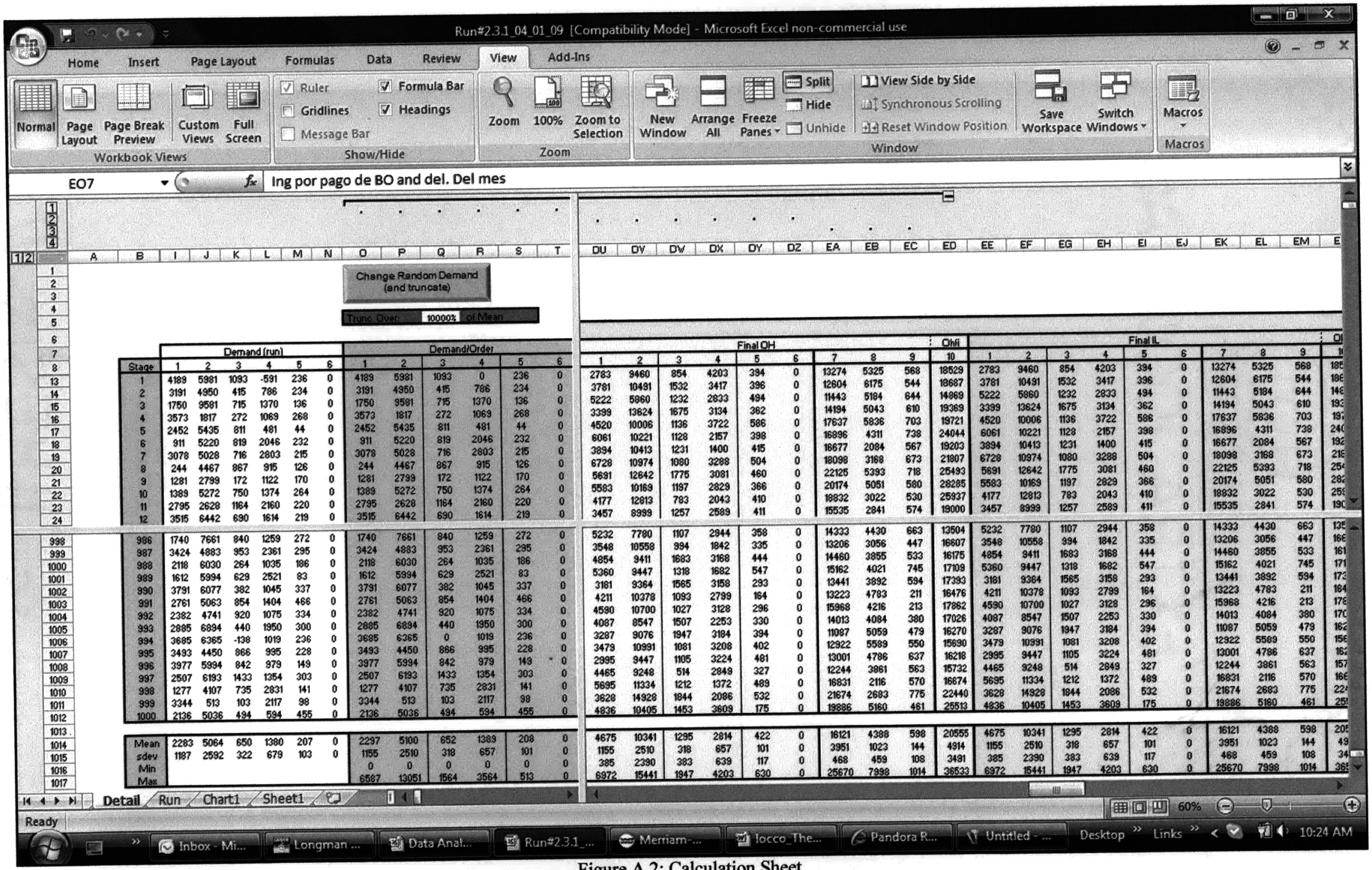
S.T.	P.T	Mean	Sdev	P.S	S.S
0	1	1401	701	2802	2802

S.T.	P.T	Mean	Sdev	P.S	S.S.
0	1	210	105	420	420

S.T	P.T	Mean	Sdev	P.S	S.S
0	1	0	0	0	0

	Mean	Sdev	P.S.	S.S.
Total	9731.0	2929.2	38926	56042

Figure A.1: Model Data Sheet



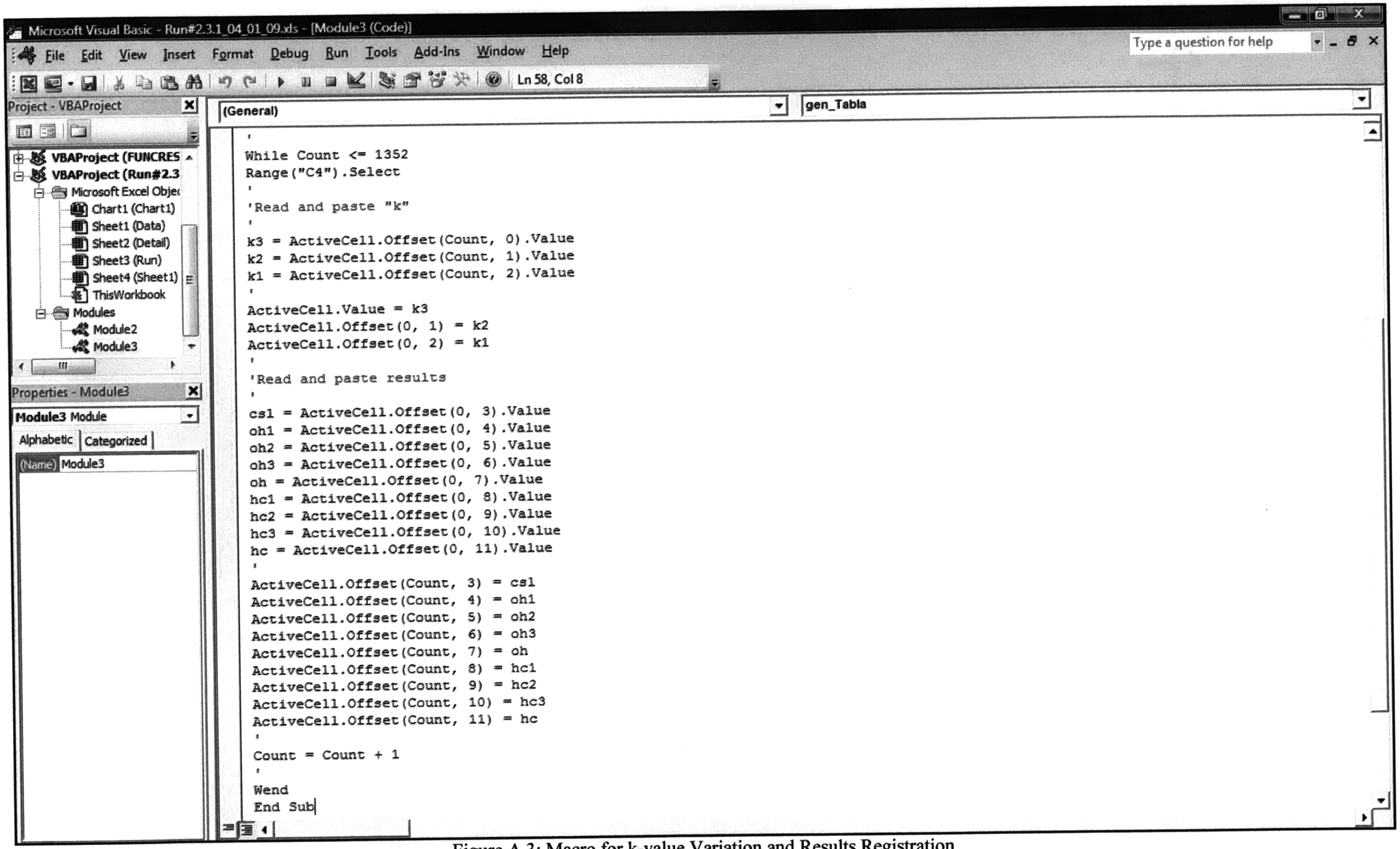
EO7 Ing por pago de BO and del. Del mes

Trunc. Over: 10000% of Mean

	Demand (run)						Demand/Order					
Stage	1	2	3	4	5	6	1	2	3	4	5	6
1	4189	5981	1093	-591	236	0	4189	5981	1093	0	236	0
2	3191	4950	415	786	234	0	3191	4950	415	786	234	0
3	1750	9581	715	1370	136	0	1750	9581	715	1370	136	0
4	3573	1817	272	1069	268	0	3573	1817	272	1069	268	0
5	2452	5435	811	481	44	0	2452	5435	811	481	44	0
6	911	5220	819	2046	232	0	911	5220	819	2046	232	0
7	3078	5028	716	2803	215	0	3078	5028	716	2803	215	0
8	244	4467	867	915	126	0	244	4467	867	915	126	0
9	1281	2799	172	1122	170	0	1281	2799	172	1122	170	0
10	1389	5272	750	1374	264	0	1389	5272	750	1374	264	0
11	2795	2628	1164	2160	220	0	2795	2628	1164	2160	220	0
12	3515	6442	690	1614	219	0	3515	6442	690	1614	219	0
986	1740	7661	840	1259	272	0	1740	7661	840	1259	272	0
987	3424	4883	953	2361	295	0	3424	4883	953	2361	295	0
988	2118	6030	264	1035	186	0	2118	6030	264	1035	186	0
989	1612	5994	629	2521	83	0	1612	5994	629	2521	83	0
990	3791	6077	382	1045	337	0	3791	6077	382	1045	337	0
991	2761	5063	854	1404	466	0	2761	5063	854	1404	466	0
992	2382	4741	920	1075	334	0	2382	4741	920	1075	334	0
993	2885	6894	440	1950	300	0	2885	6894	440	1950	300	0
994	3685	6365	-138	1019	236	0	3685	6365	0	1019	236	0
995	3493	4450	866	995	228	0	3493	4450	866	995	228	0
996	3977	5994	842	979	149	0	3977	5994	842	979	149	0
997	2507	6193	1433	1354	303	0	2507	6193	1433	1354	303	0
998	1277	4107	735	2831	141	0	1277	4107	735	2831	141	0
999	3344	513	103	2117	98	0	3344	513	103	2117	98	0
1000	2136	5036	494	594	455	0	2136	5036	494	594	455	0
Mean	2283	5064	650	1380	207	0	2297	5100	652	1389	208	0
sdev	1187	2592	322	679	103	0	1155	2510	318	657	101	0
Min							0	0	0	0	0	0
Max							6587	13051	1564	3564	513	0

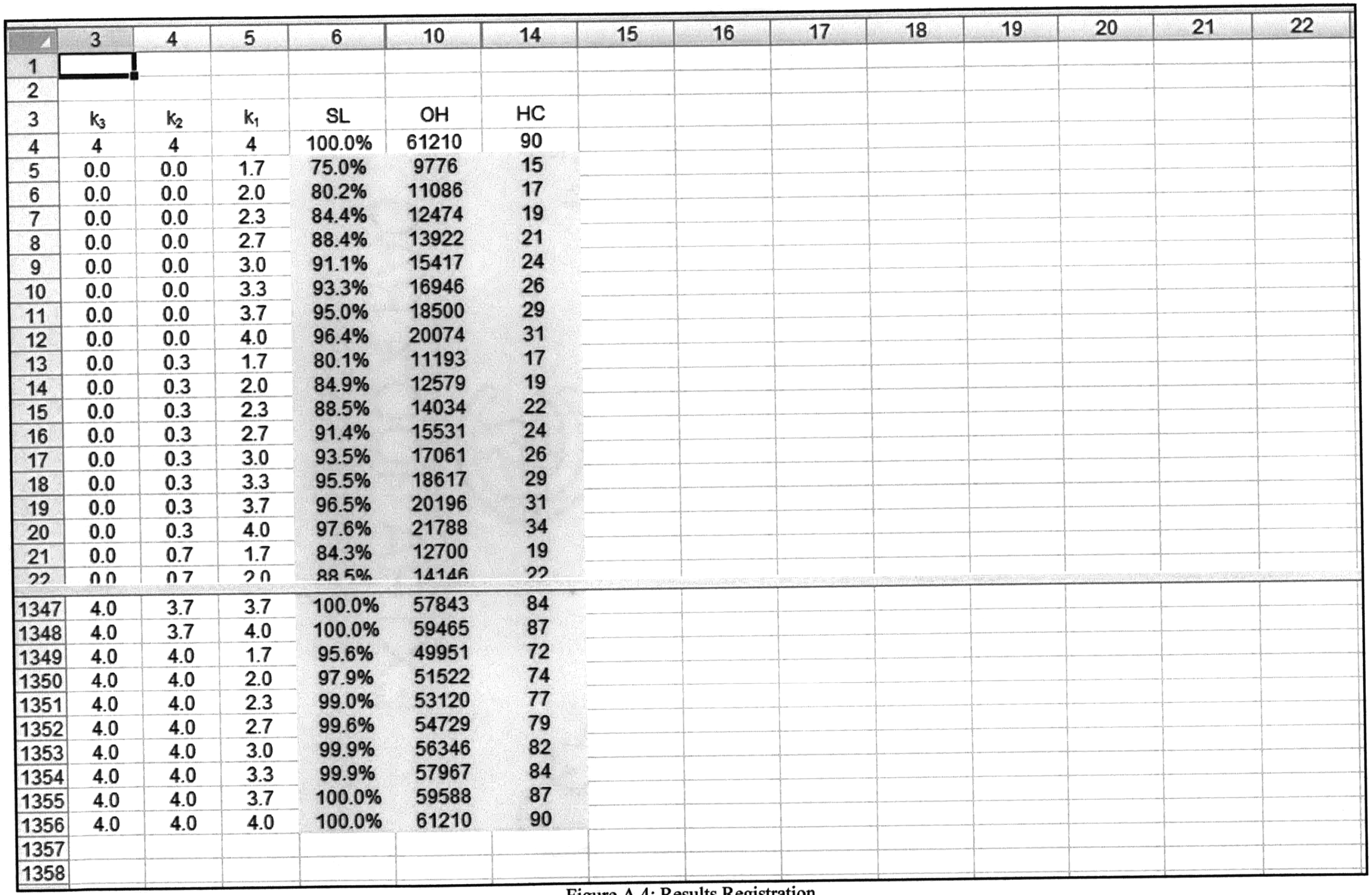
	Final OH									Ohfi	Final IL								
Stage	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9
1	2783	9460	854	4203	394	0	13274	5325	568	18529	2783	9460	854	4203	394	0	13274	5325	568
2	3781	10491	1532	3417	396	0	12604	6175	544	18687	3781	10491	1532	3417	396	0	12604	6175	544
3	5222	5860	1232	2833	494	0	11443	5184	644	14869	5222	5860	1232	2833	494	0	11443	5184	644
4	3399	13624	1675	3134	362	0	14194	5043	610	19369	3399	13624	1675	3134	362	0	14194	5043	610
5	4520	10006	1136	3722	586	0	17637	5836	703	19721	4520	10006	1136	3722	586	0	17637	5836	703
6	6061	10221	1128	2157	398	0	16896	4311	738	24044	6061	10221	1128	2157	398	0	16896	4311	738
7	3894	10413	1231	1400	415	0	16677	2084	567	19203	3894	10413	1231	1400	415	0	16677	2084	567
8	6728	10974	1080	3288	504	0	18098	3168	673	21807	6728	10974	1080	3288	504	0	18098	3168	673
9	5691	12642	1775	3081	460	0	22125	5393	718	25493	5691	12642	1775	3081	460	0	22125	5393	718
10	5583	10169	1197	2829	366	0	20174	5051	580	28285	5583	10169	1197	2829	366	0	20174	5051	580
11	4177	12813	783	2043	410	0	18832	3022	530	25937	4177	12813	783	2043	410	0	18832	3022	530
12	3457	8999	1257	2589	411	0	15535	2841	574	19000	3457	8999	1257	2589	411	0	15535	2841	574
986	5232	7780	1107	2944	358	0	14333	4430	663	13504	5232	7780	1107	2944	358	0	14333	4430	663
987	3548	10558	994	1842	335	0	13206	3056	447	16607	3548	10558	994	1842	335	0	13206	3056	447
988	4854	9411	1683	3168	444	0	14460	3855	533	16175	4854	9411	1683	3168	444	0	14460	3855	533
989	5360	9447	1318	1682	547	0	15162	4021	745	17109	5360	9447	1318	1682	547	0	15162	4021	745
990	3181	9364	1565	3158	293	0	13441	3892	594	17393	3181	9364	1565	3158	293	0	13441	3892	594
991	4211	10378	1093	2799	164	0	13223	4783	211	16476	4211	10378	1093	2799	164	0	13223	4783	211
992	4590	10700	1027	3128	296	0	15968	4216	213	17862	4590	10700	1027	3128	296	0	15968	4216	213
993	4087	8547	1507	2253	330	0	14013	4084	380	17026	4087	8547	1507	2253	330	0	14013	4084	380
994	3287	9076	1947	3184	394	0	11087	5059	479	16270	3287	9076	1947	3184	394	0	11087	5059	479
995	3479	10991	1081	3208	402	0	12922	5589	550	15690	3479	10991	1081	3208	402	0	12922	5589	550
996	2995	9447	1105	3224	481	0	13001	4786	637	16218	2995	9447	1105	3224	481	0	13001	4786	637
997	4465	9248	514	2849	327	0	12244	3861	563	15732	4465	9248	514	2849	327	0	12244	3861	563
998	5695	11334	1212	1372	489	0	16831	2116	570	16674	5695	11334	1212	1372	489	0	16831	2116	570
999	3628	14928	1844	2086	532	0	21674	2683	775	22440	3628	14928	1844	2086	532	0	21674	2683	775
1000	4836	10405	1453	3609	175	0	19886	5160	461	25513	4836	10405	1453	3609	175	0	19886	5160	461
Mean	4675	10341	1295	2814	422	0	16121	4388	598	20555	4675	10341	1295	2814	422	0	16121	4388	598
sdev	1155	2510	318	657	101	0	3951	1023	144	4914	1155	2510	318	657	101	0	3951	1023	144
Min	385	2390	383	639	117	0	468	459	108	3491	385	2390	383	639	117	0	468	459	108
Max	6972	15441	1947	4203	630	0	25670	7998	1014	36533	6972	15441	1947	4203	630	0	25670	7998	1014

Figure A.2: Calculation Sheet



```
'
While Count <= 1352
Range("C4").Select
'
'Read and paste "k"
'
k3 = ActiveCell.Offset(Count, 0).Value
k2 = ActiveCell.Offset(Count, 1).Value
k1 = ActiveCell.Offset(Count, 2).Value
'
ActiveCell.Value = k3
ActiveCell.Offset(0, 1) = k2
ActiveCell.Offset(0, 2) = k1
'
'Read and paste results
'
cs1 = ActiveCell.Offset(0, 3).Value
oh1 = ActiveCell.Offset(0, 4).Value
oh2 = ActiveCell.Offset(0, 5).Value
oh3 = ActiveCell.Offset(0, 6).Value
oh = ActiveCell.Offset(0, 7).Value
hc1 = ActiveCell.Offset(0, 8).Value
hc2 = ActiveCell.Offset(0, 9).Value
hc3 = ActiveCell.Offset(0, 10).Value
hc = ActiveCell.Offset(0, 11).Value
'
ActiveCell.Offset(Count, 3) = cs1
ActiveCell.Offset(Count, 4) = oh1
ActiveCell.Offset(Count, 5) = oh2
ActiveCell.Offset(Count, 6) = oh3
ActiveCell.Offset(Count, 7) = oh
ActiveCell.Offset(Count, 8) = hc1
ActiveCell.Offset(Count, 9) = hc2
ActiveCell.Offset(Count, 10) = hc3
ActiveCell.Offset(Count, 11) = hc
'
Count = Count + 1
'
Wend
End Sub
```

Figure A.3: Macro for k-value Variation and Results Registration



	3	4	5	6	10	14	15	16	17	18	19	20	21	22
1														
2														
3	k_3	k_2	k_1	SL	OH	HC								
4	4	4	4	100.0%	61210	90								
5	0.0	0.0	1.7	75.0%	9776	15								
6	0.0	0.0	2.0	80.2%	11086	17								
7	0.0	0.0	2.3	84.4%	12474	19								
8	0.0	0.0	2.7	88.4%	13922	21								
9	0.0	0.0	3.0	91.1%	15417	24								
10	0.0	0.0	3.3	93.3%	16946	26								
11	0.0	0.0	3.7	95.0%	18500	29								
12	0.0	0.0	4.0	96.4%	20074	31								
13	0.0	0.3	1.7	80.1%	11193	17								
14	0.0	0.3	2.0	84.9%	12579	19								
15	0.0	0.3	2.3	88.5%	14034	22								
16	0.0	0.3	2.7	91.4%	15531	24								
17	0.0	0.3	3.0	93.5%	17061	26								
18	0.0	0.3	3.3	95.5%	18617	29								
19	0.0	0.3	3.7	96.5%	20196	31								
20	0.0	0.3	4.0	97.6%	21788	34								
21	0.0	0.7	1.7	84.3%	12700	19								
22	0.0	0.7	2.0	88.5%	14146	22								
1347	4.0	3.7	3.7	100.0%	57843	84								
1348	4.0	3.7	4.0	100.0%	59465	87								
1349	4.0	4.0	1.7	95.6%	49951	72								
1350	4.0	4.0	2.0	97.9%	51522	74								
1351	4.0	4.0	2.3	99.0%	53120	77								
1352	4.0	4.0	2.7	99.6%	54729	79								
1353	4.0	4.0	3.0	99.9%	56346	82								
1354	4.0	4.0	3.3	99.9%	57967	84								
1355	4.0	4.0	3.7	100.0%	59588	87								
1356	4.0	4.0	4.0	100.0%	61210	90								
1357														
1358														

Figure A.4: Results Registration

Appendix B: Simulations' Confidence Intervals

The confidence interval around the performance metrics from the simulations is calculated using the general equation (Winston, 2004):

$$Confidence\ Intervals = \overline{X} \pm t_{(\alpha/2,n-1)}\sqrt{\frac{S^2}{n}} \qquad \text{(Eq. B.1)}$$

where

- $\overline{X}$: mean value of the variable simulated.
- $t(\alpha/2,n-1)$: t-value of the Student's t-distribution as a function of the probability and the degrees of freedom.
- $\alpha/2$: probability.
- n: degrees of freedom.

Table B.1 shows the values to compound the confidence interval. Average service level (Avr. SL) and average holding cost (Avr. HC) are the same as Table 4.7. The standard deviations of these variables are shown as "SD SL" and "SD OH". Finally, the values to determine the interval of confidence for a 95% of probability are shown in the last two columns.

Table B.1: Calculation of the Confidence Interval's Parameter

Model	Strategy	k_{sim}			Avr.SL	Avr. HC	SD SL	SD HC	95% IC SL (+/-)	95% IC HC (+/-)
		Echelon3	Echelon2	Echelon1						
Single-Echelon	1	0.00	0.00	4.03	96.5%	352	8.8%	115	0.5%	7.1
	2	0.00	2.60	1.64	94.3%	321	10.8%	113	0.7%	7.0
	3	1.64	0.00	2.85	96.6%	313	8.4%	116	0.5%	7.2
Echelon-Inventory	95/99/99 %	0.35	1.31	1.64	91.7%	251	13.1%	111	0.8%	6.9
	99/99/99 %	0.35	0.67	2.33	93.8%	268	12.0%	111	0.7%	6.9
Graves-Willems	L,H,H cost	1.64	1.64	1.64	94.8%	320	10.2%	118	0.6%	7.3
	L,L,H cost	0.00	2.60	1.64	94.3%	–	10.8%	113	0.7%	7.0
	L,L,L cost	0.00	0.00	4.03	96.5%	–	8.8%	113	0.5%	7.0

For example, for the single-echelon strategy 1 SL and belong with a 95% of confidence to the interval 96.5 +/- 7.1% and it OC to the interval 352 +/- 7.1 $ per week.