An Application of a Cost Minimization Model in Determining Safety Stock Level and Location

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ABSTRACT

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The application of a lean philosophy to supply chains has received increasing attention from researchers in the last few decades. Manufacturers are one of the most important contributors in the supply chain and inventory plays a critical role for them to become lean. Implementing lean in manufacturers' inventory systems requires establishing efficient logistics systems.

This research addresses optimization of the inventory and safety stock across the supply chain and applying their models in a real-world manufacturer case company. We present a constrained non-linear optimization safety stock model with the objective of logistics cost minimization which results in the optimal level and location of safety stock across the chain. A safety stock simulation model is provided as well to sustain the results of the optimal safety stock for the case company. Finally, an inventory simulation model is provided to set target for the company's inventory towards leanness and improve its turnover. Numerical examples are presented to analyze the safety stock optimization model performance while implementing in the case company.

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Chapter One

Introduction

1.1 Background

In recent decades, the lean methodology and the development of its principles and concepts have widely been applied in supply chain management. Contributors of a supply chain, no matter to which industry they belong, aim to follow the lean philosophy to make their business processes more and more efficient in order to survive on the market. Lean thinking is essentially about increasing the efficiency, eliminating waste, and bringing new ideas by using empirical methods.

Seven original wastes to be tackled were introduced in the lean philosophy: transportation, motion, waiting, over-processing, over-production, defects, and inventory. Manufacturers are one of the most important contributors in the supply chain and inventory plays a paramount role in their efforts to become lean. Therefore, one of the most important strategies to become lean for manufacturers is having efficient inventory within their chain. 27% of companies have accepted and practiced inventory optimization policies (Aberdeen, 2004).

The best-in-class companies gained improvements by applying inventory management practices such as rethinking where to hold finished goods across the network, optimizing inventory policies for each item location, among others and these improvements could increase by applying technologies such as supplier collaboration technology, multi-echelon inventory optimization tools, and so on to these practices. For example, companies using a tool to optimize item-location level planning were five times more likely to have lower holding cost in comparison to the industry average, or companies that used visibility were twice as likely to have below average holding cost as those that do not apply such practices (Aberdeen, 2004).

There are different inventory drivers, such as the level of supply chain collaboration and visibility, forecast accuracy, order pattern, and safety stock policy, among others. Hence, proper management of inventory and consequently safety stock as one of its drivers has become a critical objective towards achieving leanness. In fact, managing inventory efficiently requires appropriate management of safety stock in order to protect against increasing the stretch in the breaking points of the supply chain, which in turn can result in possible reduction of inventory.

Having an efficient level of inventory is a step towards increasing the inventory turnover in companies. According to the definition of turnover, decreasing the level of inventory helps to increase the turns. One of the approaches towards reduction of inventory especially in Just In Time (JIT) environments is reducing lot sizes. But, smaller lot sizes will lead to uncertainties and consequently stockouts (Natarjan and Goyal, 1994). Therefore, safety stock is needed to protect against these kinds of uncertainties.

An optimization model of safety stock for efficiency can be built on different objectives. Minimization cost, maximization service level, and aggregate considerations are examples of such objectives (Silver, Pyke and Peterson, 1998). Meanwhile, optimal determination approaches based on cost and service level objectives are more appropriate for practical applications (Inderfurth, 1991). One of the vital goals of the enterprise is to maximize earnings under certain investment conditions (Long et al., 2009). Since reducing costs of materials, equipment, and labor is difficult at best in today's competitive market, enterprises are more interested in targeting logistics costs in this regard (Long et al., 2009). Logistics costs are mainly related to procurement and supply, manufacturing process, and after sales service. Indeed, determining the appropriate location and size of safety stock would be an approach to protect against supply chains' uncertainties at an acceptable cost.

"Supply chain is the lifeblood of the corporation and sales revenue depends on the supply chain delivering product availability" (Dittman, Slone and Mentzer, 2010). Indeed, product availability is a critical measure of the performance of logistics and supply chain (Coyle, Bardi and Langley, 2009). Any obstacles at any node and level of the supply chain can result in unavailability of products to their customers. There are different issues that cause disruptions and unavailability of products in the supply chain, as for example variability, whether in demand or lead time; quality issues; or internal and external issues such as low delivery performances, improper scheduling, inadequate product capacity, poor maintenance, among others. Figure 1.1 is a schematic of a supply chain with its nodes as different tiers of suppliers, producer, assembly, distributors, and customer. Any actions taken by any member of the chain can affect the profitability of the others. Therefore, companies have great interest in having better coordination among the contributors of their supply chain (Silver, Pyke and Peterson, 1998). Safety stock is essential to compensate for the weakness of the supply chain for part availability.

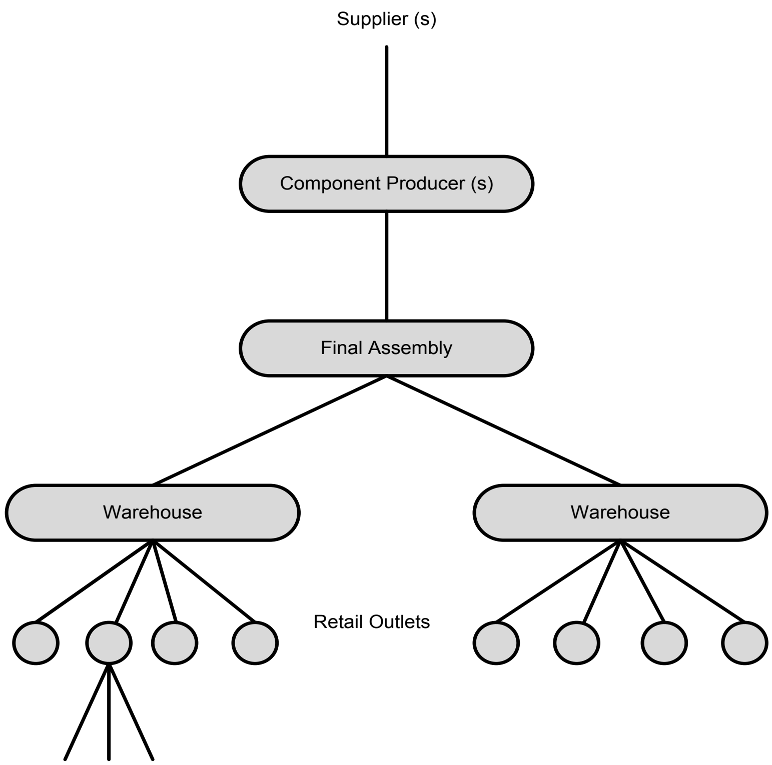


Figure 1.1 A schematic of a supply chain

Finally, if safety stock, as one of the most important driver of inventory, is optimized, inventory can be optimized accordingly.

1.2 Research problem

The problem that we face in this research is applying lean philosophy to the inventory and safety stock within the supply chain for the purpose of reducing logistics costs. Therefore, topics of lean, supply chain management and inventory are defined briefly here.

The foundation of lean was laid in the Japanese automotive sector. Lean production was developed by Toyota; its ultimate goal is to eliminate any existing waste in the production system (Jie, 2010). In the pivotal books, "The machine that changed the world" (Womack, Jones and Roos, 1991) and "Lean Thinking" (Womack and Jones, 2003), the authors introduced five essential principles of lean thinking which are value definition, value stream definition, process flow, pull, and perfection. Lean thinking emphasizes waste removal, where waste is defined as any inaccuracy in the process or any action that does not add value. In other words, lean is meeting customer requirements accurately by removing waste and eliminating any inaccuracy in a process (Jie, 2010). Value as the first principle of lean is identified only by the end customer and it is expressed in terms of a product or a service or both of them that meets the requirements of the customer. Value stream is the aggregation of all actions needed to bring a specific product through problem-solving task, information management task, and physical transformation task (Womack and Jones, 2003). Flow is about ensuring the smoothness of whole processes. Pull means produce only once customer ask for it. Perfection is about attempts for continuous improvement for reducing cost, time, space, and so forth. Value stream mapping as a tool of lean is a method to depict material and information flow throughout whole the chain for both value added and non-value added processes. Value stream mapping makes the identification of the wastes easier.

Some of the approaches to applying lean in production systems are U- type layouts, 5S management, visual management, kanban management, equipment maintenance, among others.

Supply chain management has been a popular topic for decades now as it not only results in many valuable improvements such as reduction in costs and decrease in cycle time, but it also makes companies more competitive in today's dynamic market (Viswanadham and Gaonkar, 2003). Supply chain management is an integration of the business processes from the suppliers to the end customer which provides products, services, and information and also adds value for the end user and all the stakeholders (Lambert and Cooper, 2000).

There is a definition for supply chain management adopted by Council of Supply Chain Management Professionals (CSCMP) as the organization's official one (Mentzer et al., 2001): "Supply Chain Management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, Supply Chain Management integrates supply and demand management within and across companies."

Supply chain management has been studied from many different points of view such as finance, marketing, logistics, information technology, environment, financial law and economics, electronic commerce, and business administration. The logistics area consists of all plans and their implementation and it also consists of controlling the inventory flow and its efficiency from the first point until the end customer (Lambert and Cooper, 2000).

Manufacturing has become important in developed countries as it is the lifeblood of many financial services and consulting firms. On the other hand, inventory management has been highlighted for managers in the manufacturing environment to be competitive (Silver, Pyke and Peterson, 1998).

Inventories in different industries due to their different production processes concentrates in different areas. Reducing the amount of direct manufacturing labor expended per unit of output was a way for productivity improvement historically and the portion of the cost related to this factor has been reduced in recent years. Furthermore, the ratio of the purchased parts has been increased which makes the raw material inventories a good area for productivity improvement. Meanwhile, just-in-time manufacturing has proved that work in process inventories is another excellent area for improvement. Finally, researches in supply chain management have indicated that there are many opportunities in finished goods inventory and distribution areas for improvement (Silver, Pyke and Peterson, 1998).

Inventory consists of raw material, works in process (WIP), semi-finished part, and finished part that are ready to be sold and are part of the asset of the business. Inventory is one of the most important factors in the business as its turnover is a metric for assessing the revenue and earnings of the shareholders of the business.

Inventory management is an important topic for the business. Having lots of inventory is not desired as it will increase the holding costs; on the other hand, having little inventory is not good either as it may cause shortage, losing sale and risk.

There are different measures of effectiveness in the area of the inventory such as cost, customer service level, recognition of the constraints and limitations among others. Selections of these effectiveness measures depend on the management objectives.

In summary, inventory control is a critical topic in applying lean philosophy in a manufacturing area towards the goal of proper management of its supply chain and reducing its associated costs.

1.3 Objectives and methodology

The objective of this thesis is to recommend how firms can make their inventory and safety stock efficient across the supply chain in order to become lean, reduce logistics costs, and increase inventory turns.

Since efficient inventory requires efficient safety stock as a prerequisite, a safety stock optimization model is developed. The model determines the optimal level and location of the safety stock within the supply chain while minimizing logistics costs. It is a constrained non-linear model with the decision variable of safety stock and constraints on the delivery performances of each stage of the supply chain. The model is then developed using Lingo optimization software and applied to a real-life company.

A safety stock simulation model is provided as well to support the results of the optimization by introducing and assessing the relevant metrics from the case study. This simulation model sustains the results obtained from the optimization model.

Finally, an inventory simulation model is used to determine efficient inventory targets for leanness and to increase inventory turns. The model was developed using SQL programming according to the hypotheses and assumptions made by the case company.

1.4 Organization of the thesis

This thesis is organized into five chapters. Following the introductory chapter, Chapter two provides a detailed literature review. In Chapter three, the problem description and model formulation for both safety stock and inventory are presented and the solution approaches are discussed. Some numerical examples of the safety stock optimization model are presented and solved in Chapter four and the results are analyzed. Finally, in Chapter five, conclusions and future research are presented.

Chapter Two

Literature Review

2.1 Lean supply chains

In today's competitive environment, applying the lean paradigm has been extended to the field of supply chain management. Taylor (1999) describes the Parallel Incremental Transformation Strategy (PITS) which is a disaggregated approach that applies the lean philosophy to the supply chain in order to sustain supply chain improvement. PITS is a methodology that tries to reach its objective by educating personnel, getting them involved and motivating them in self-generating and self-sustaining incremental improvement initiatives. The six main important points of these initiatives are education and awareness, waste analysis, creating an appropriate organizational structure, value stream mapping, incremental improvement, and evolutionary development of a supply chain strategy.

Adamides et al. (2008) present an integrated suite of internet-based software called Co-LEAN to improve lean networks by providing the required infrastructures for solving their problems. The authors claim that lean supply chain management has to move towards contractual relations to reach improvement which requires shared understanding, shared commitment and also shared goals that will be satisfied by proper information and communication technologies. They also claim that organizations can integrate their processes at the operational level without much difficulty using these techniques through appropriate knowledge and information exchange.

Crino, McCarthy and Carier (2007) developed the lean six sigma methodology (LSS) to improve the performance of a company's supply chain continuously as lean focuses on waste reduction and six sigma focuses on variability reduction. Through this combination, six sigma compensates for the weakness of lean through statistical analysis.

Wu and Wee (2009) explain four steps of a problem solving process for implementing a lean supply chain and also tried to show the reason behind Toyota's success by using the value stream mapping (VSM) tool, among others, through a case study. They show the possibility of continuous improvement through gap analysis between the current state map (CSM) and the future state map (FSM). They define some notations such as First Time Through, Dock To Dock Time, Overall Equipment Effectiveness, Value Rate, Value Added Time, Non Value Added Time, and Takt Time. They demonstrate the four steps of problem solving as problem finding, idea finding, obstacle finding, and solution finding in order to develop the CSM and FSM. They showed the VSM by demonstrating the difference between the values of measurable indices such as cost, quality, and lead time as they were in the CSM as compared to the FSM. Finally, the authors highlighted the focus of Toyota on the prevention of over production instead of batch building as its difference from traditional thinking. In other words, companies other than Toyota were interested in short term strategies such as mass production which result in short term financial goals, while Toyota aimed to apply VSM to eliminate wastes and implement one piece flow with a long term philosophy.

Wu (2003) compares the lean suppliers with non-lean suppliers to show whether there are significant differences in their performances or not. His research findings indicate that lean suppliers have performed much better and received more acceptable results in many areas such as production, distribution, transportation, customer-supplier relationship, and communications even with the same constraints and resources. By using lean techniques, small-lot production, short delivery lead time, high quality, labor flexibility, close coordination with suppliers and customers, are among the benefits.

2.2 Efficient supply chain (Lean, Agility, and Leagile)

Supply chain management is the collaborative effort of multiple channel members to design, implement, and manage seamless value-added processes to meet the real needs of the end customer. More recently, the lean philosophy, made up of well-known concepts, has been applied in areas other than manufacturing, such as in the supply chain. Lean is a highly evolved managing method to increase the efficiency, productivity, and also to improve the quality of the products and/or services of the organizations and ultimately increase the profit of the supply chain by cost reduction. Agility is another paradigm of supply chain which maximizes profit by making the supply chain responsive to the market. The combination of these two paradigms is called “Leagile” which results in another type of supply chain which proposes determining the decoupling point and applying lean processes upstream and agile processes downstream.

Naylor, Naim and Berry (1999) studied the lean and agile paradigms and discussed their similarities as well as their differences. They demonstrated which paradigm is more suitable for which kind of product, or which market knowledge is more highlighted in each. They proved through case studies that a combination of these two manufacturing paradigms is much more profitable in a supply chain by selecting an appropriate decoupling point according to the chosen strategy rather than considering them in isolation. In fact, agility is appropriate for dealing with demand variability and on the other hand, lean is suited for level scheduling. Therefore, lean is applicable to the upstream portion of the supply chain and agility is applicable to the downstream portion of the chain to protect against demand variability.

Qi, Xuejun and Zhiyong (2007) compare two paradigms of lean and agility and analyze their preferences and applications according to the type of product involved and also by considering the market qualifiers and market winners. They explain how to implement leagile paradigm in the supply chain by finding the best decoupling points of material and information.

Mason-Jones, Naylor and Towill (2000) discuss applying the lean paradigm, agile paradigm, and both simultaneously in three different case studies. Their study shows that different paradigms could be selected for the supply chain to optimize performance according to the market need.

Agarwal, Shankar and Tiwari (2006) illustrate the attributes of lean, agile, and leagile supply chains and compare them. They also provide a framework for modeling the performance of these three paradigms which helps decision makers to analyze variables such as lead time, cost, quality, and service level by using the Analytical Network Process (ANP) approach that results in the improvement of the supply chain. The strength of using the ANP approach is that not only does it demonstrate the influence of each performance dimension on the supply chain, but also the effect of each performance determinate. ANP is suitable for a multi-criteria decision environment.

In recent decades, manufacturers and non-manufacturers have been facing many challenges such as rapid changes, uncertainty, demands for different kinds of products or services that should be satisfied at the right time by the right quantity with the right quality, among others. Hence, companies could survive on the market by dealing with these challenges properly. Consequently, as Supply Chain Management (SCM) focuses on material, information and cash flow and as it is believed that "it is supply chains that compete not the companies" (Christopher and Towill, 2001), selecting an appropriate chain model with the proper strategy becomes more and more necessary and important. This strategy should consider customer satisfaction and also market place understanding.

2.3 Efficient inventory models in supply chain

There are different classifications for inventory models such as deterministic versus stochastic, single versus multi echelon, periodic versus continuous review, discrete versus continuous demand, backorders versus lost sales, fixed cost versus no fixed cost, and lead time versus no lead time, among others.

Costs related to inventory are holding cost, stock out penalty, fixed cost, and purchase cost. There is a basic tradeoff between service level and inventory cost which is shown in Figure 2.1.

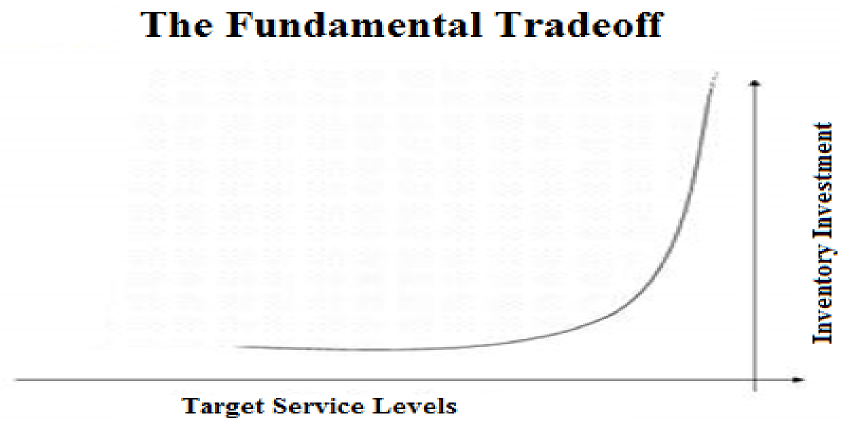


Figure 2.1 Tradeoff between service level and cost

Increased levels of inventory reduce stock outs, but lead to low turnover. Lower inventory reduces inventory costs, but often at the expense of loss of sales. Therefore, determining the right balance that maximizes profitability is a challenge that every business faces.

Keeping inventory strategies up to date with current conditions is important in order to have reasonable financial performance. It is known that best in class companies are 2.5 times as likely as laggard companies to update their inventory strategy multiple times a year (Aberdeen, 2004). There are so many challenges in implementing and improving inventory management, but it is also essential to have metrics in place to measure the improvement towards the optimal inventory. Although it is complex to accurately assess cost, benefits and risks of changing inventory strategies because they are directly connected to the customer satisfaction, revenue, and so forth, there exist some modeling tools that are very useful to accurately simulate the impacts of these changes and also to optimize business objectives. There are different supply chain inventory tactics that companies apply such as lean synchronization technology, warehouse system, item location policy optimization tool for finished goods, visibility system, among others.

2.4 Efficient safety stock models in single and multi-echelon networks

Safety stock is the inventory which is kept as a buffer to protect against time mis-match between supply and demand. It is also held to protect against variability, which exists whether in supply or demand. And finally this buffer is used as a tradeoff between service level and inventory cost.

Different methods for computing safety stock in the Just In Time (JIT) environments are presented by Natarajan et al. (1994). These methods deal with objectives related to service level, expected number of stockouts, tradeoffs between stocking out and carrying extra buffer, minimization of total cost which is comprised of set-up, holding, and shortage costs.

According to the literature, there are different approaches and methods for determining safety stock under different situations. Determination of the optimal level and location of safety stock in a supply chain with different stages and a stochastic environment is a very complex task; therefore, most of the models and approaches developed in this regard have applied certain simplifying assumptions. Some of these approaches are applicable for only a specific inventory system, some of them limit the distribution of demand, and some of them exclude the suppliers' variability.

Minner (1997) uses dynamic programming algorithms to find the optimal combinations of coverage times with the target of minimizing the average holding costs in serial, divergent, and convergent inventory systems. In this paper, it is assumed that customer demand is normally distributed and correlations between demands are permitted. One of the outcomes of this paper is that concentrating safety stocks at the first and final stages would be optimal for a serial system with a high enough service level.

A linear programming model with the objective of establishing a tradeoff among plan change, carrying, and shortage costs under resource constraints for a multi-item production system is presented by Kanyalkar and Adil (2009). Plan change cost is related to the instabilities occurring under a rolling schedule. These instabilities in the chain affect costs such as setup and expediting costs and they also affect material plans like shortage or excess of components.

Jung et al. (2008) present a linear programming formulation which includes the control variables of safety stock with the purpose of minimization of the total supply chain's inventory while meeting the service level target. This model incorporates the nonlinear performance functions, the interdependence between the service level at upstream and downstream stages of the supply chain and also the safety capacity constraint. Some of the assumptions applied in this model are normally distributed demand, zero lead time at the warehouse, and constant production capacity. In addition, it is assumed that raw material and transportation means in any size are always available.

A dynamic model of the safety stock assuming a Vendor Managed Inventory (VMI) system is presented by Li and Li (2009). Under the VMI system, the uncertainties related to the efficiency of the supplier disappear and the model considers only the variability sourced by demand.

Patel, Rodrigues and Kamath (2010) present the dynamics of a model of optimizing safety stock for a small-scale aluminum utensil manufacturing industry. This model takes into account the factors of demand, production rate, delay, and waste time. This paper concentrates on the bullwhip effect in a manufacturing supply chain and tries to reduce it by increasing safety stock.

Zhao, Lai and Lee (2001) use a simulation approach to evaluate alternative methods of determining the level of safety stock based on historical forecasting errors in multilevel MRP systems. In addition, the relation between the safety stock multipliers and different system performance measures such as total cost, service level, and schedule instability in different methods are analyzed.

A study done by Badinelli (1986) focuses on combining stockout and holding costs functions towards determining the optimal safety stock. It also presents a technique for estimating the stockout cost with a decision maker's disvalue function as there is uncertainty for decision makers for the trade-offs between holding inventory and being in shortage.

An approximation model for safety stock in a two echelon distribution system is provided by Desmet, Aghezzaf and Vanmaele (2010). This model tries to incorporate the variance of the retailers and the central warehouse in the replenishment lead time. It also takes into account the variance of the service time of orders at the warehouse as it has significant effect on the system's lead time variance.

Inderfurth (1991) represents a safety stock optimization model in a multi-stage problem with divergent structure and provides a dynamic programming algorithm to solve it. The analysis for the impact of the correlation of demands on safety stock allocation has also been provided. This model does not include inter-stage shortage costs by assuming possession of a certain capacity of slack resources for operating flexibility.

In the continuation of his previous work, Inderfurth (1995) extended his study to a case where demand is not only cross-product but also cross-time correlated. Cross-time correlation of demand yields a tendency to keep safety stock at the end-item level, while cross product correlation provides a tendency for holding buffer more in upstream stages. One of the results of this study is that increasing the correlation in both products and time makes the safety stock policy more expensive. This research also shows that not taking into account the demand correlation may result in incorrect sizing and positioning of safety stock in multi-stage manufacturing systems. Neglecting this may also lead to missed cost reduction opportunities.

A nonlinear integer optimization model with the objective of minimizing the total setup and inventory holding costs by considering a service level constraint has been developed by Carlson and Yano (1986). The only variability that is incorporated into the model is related to demand. In addition, it is assumed that there are no capacity constraints. The model suggests having safety stock at those stages with high setup or disruption costs.

Sitompul and Aghezzaf (2006) consider a capacitated n-stage serial chain with the base-stock policy. They put an assumption of normally distributed customer demand and abundant raw material. They also consider a maximum allowable demand. The level of inventory that can assure a certain time interval is called bounded demand. They incorporate the replenishment lead time for the safety stock calculation as the summation of the setup time of each stage and the time to get input from its upstream stage minus the time that the stage guarantees to satisfy its downstream demand. They examine and simulate the effect of the capacity restrictions to the stockout level for one stage with three levels of standard deviation. The results prove that the safety stock required for 1% stockout is proportional of service level multiply to the standard deviation. By varying the production capacity over the stages, the setup time will also affect the location of the safety stock rather than the demand. Then, they calculate the average net replenishment lead time and set the base stock to the maximum demand over the average replenishment lead time. In the end, they propose an optimization model with the objective of minimizing the holding cost of the chain's stages.

Lianfu et al. (2009) present a general model with the objective of logistics costs minimization by considering both internal and external variabilities and taking into account part availability, which is very important in the chain. The authors introduce customer service level, average and standard deviation of demand, average and standard deviation of random requirements in lead time as factors that have an effect on safety stock. Safety stock is essential to compensate the excess of demand from its expected quantity and also to compensate the lateness in the forecasted lead time. In their paper, they consider demand as a random variable based on the market changes and study the influences of safety stock factors. In order to reach a certain service level, required safety stock improves by increasing the variability of demand and lead time. On the other hand, in order to meet a certain rate of demand or lead time variability, service level must be improved to increase the safety stock. They introduce three aspects for variability in inventory that make the difference between actual demand and its average. These aspects are uncertainty of suppliers, manufacturers, and customer demand. They assume that demand is normally distributed. Then, they present a safety stock formula under the condition of fixed lead time for a manufacturing-distribution system with three levels of inventory. Safety stock is equal to the inverse function of service level multiply to the root square of the lead time multiply to the standard deviation of demand. They then perform a sensitivity analysis of the service level to the safety stock. The conclusion is that by increasing the customer service level, the required safety stock is increase as well. In addition, it has been shown that by increasing the customer service level more than 0.95, safety stock will be increased dramatically; therefore, an appropriate service level should be selected. At the same time, by increasing lead time, safety stock is improved accordingly. In the next step, they present a safety stock model while both demand and lead time are random. It has been illustrated that increasing average lead time while service level is fixed will cause the progress of safety stock. Furthermore, improving the service level while average lead time is fixed has even more influence on the growth of safety stock. The next analysis is about the impact of the standard deviation of lead time and service level on the safety stock when the average of lead time is fixed. Indeed, the standard deviation of lead time has more influence on the safety stock and it is more important as long as the service level is less than 0.95. This would be the other way around when service level becomes greater than 95%. The other analysis is about the influence of the standard deviation and average of lead time on safety stock. It has been concluded that increasing both will result in the growth of safety stock. But, the impact of the standard deviation of the lead time is greater than the influence of its average on safety stock.

Thomopoulos (2006) studied the impact of the delivery time variability on the service level and also he proposed the safety lead time required to protect against the lateness related to the lead time. The author considers the demand variability in the model as it arrives without advance notice and the supply chain must be really agile in order to respond on time. He suggests the forecast error as a way to calculate this uncertainty. The other variability that they incorporate into the model is the one related to the supplier lead time as the delivery time may be greater than the expected lead time. Safety time stock is introduced as a way to offset this latter variability. Two performance measures have been mentioned for the inventory system which are the amount of safety stock and the service level achieved. The amount of the safety stock must cover the uncertainty calculated by the forecast error of demand over the lead time. On the other hand, service level is defined as the ratio of demand filled over the total demand. The author assumes that delivery time is a mixed discrete and continuous variable. The lead time sensitivity analysis was done on the service level which shows that service level being reduced by increasing the lead time. There is also a discussion on safety time and safety time. Safety time allows system to hold added stock to compensate the lateness in delivery time. As it is assumed that forecasts are horizontal, safety time stock is calculated as the safety time multiply to the forecast of the next selected period. Therefore, total safety stock would be the summation of the safety time stock and safety stock. In the end, a sensitivity analysis of the service level with the safety time and supplier lead time was presented.

An optimization model with the purpose of minimizing the total holding and shortage costs is presented by Aleotti Maia and Qassim (1998). Then, an analytical solution is provided for finding the preferable case by comparing inventory and opportunity costs. It is concluded that holding inventory at the intermediate levels is not economical if it is solely used for reduction of the frequency of stockouts. The model from this paper is expanded for this thesis and applied in a real world case company. The reason for this selection is that the objective of this model is the same as the objective of the case company which is minimization of the cost.

2.5 Supply chain performance measurement

Measurement of the supply chain performance is critical for the success of any business as it deals with strategic, tactical, and operational planning and control. Supply chain performance determines the winner and measuring it facilitates the improvement of the overall chain's performance (Chen and Paulraj, 2004). Based on the Deloitte report, although 91 percent of North American manufacturers recognized the role of supply chain management as a critical one for organizational success, only 2 percent of them are in the world-class range for their supply chains (Thomas, 1999). Measuring supply chain performance is challenging in the sense of integrating quantitative and qualitative measurements and also making a linkage between strategy and performance measurement (Shepherd and Gunter, 2006).

Gunasekaran et al. (2004) developed a framework for supply chain performance measurement and metrics. They claimed the reason that many companies have not succeeded in maximizing their supply chain's potential is because of failing to develop the performance measures and metrics for enhancing the efficiency of their supply chain. They categorized the performance metrics into order planning, evaluation of supply link, metrics at production level, evaluation of delivery link, measuring customer service, and logistics cost.

Xia, Ma and Lim (2007) proposed an analytic hierarchy process (AHP) based methodology for supply chain performance measurement. They introduced four supply chain strategies that companies applied in case of competing in the market which are lean supply chain, agile supply chain, leagile supply chain, and adaptive supply chain. Then, they introduced the commonly used supply chain attributes that are reliability, responsiveness, flexibility, re-configurability, and cost. After that, they weighted these different attributes in each different supply chain strategy. They also used fuzzy logic to measure the qualitative measures and integrated them with the quantitative ones.

Beamon (1999) categorized the supply chain performance measures based on the literature to cost and combination of cost and customer responsiveness. The measure of cost consists of inventory cost and operating cost. On the other hand, the other measure includes stockput probability, lead time, and fill rate. He summarized the models for supply chain performance existing in the literature and introduced the measures that each model used which are cost, time activity, customer responsiveness, and flexibility. Then, they evaluated the performance measure systems with a single supply chain measure and the systems with joint measures. Systems with a single measure are not desired as they ignore the interactions between the supply chain characteristics. The author claimed that each supply chain should emphasize three measures: resources, output, and flexibility. The measure of resources is generally about the cost and its goal is increasing efficiency. Output measures customer responsiveness and its objective is improving the customer service level. The measurement of flexibility aims to give the system the ability to respond to the changes in the environment. The authors finally introduced two measures of flexibility which are volume flexibility and delivery flexibility to measure supply chain performance.

2.6 Summary

According to the literature review, applying a lean methodology within the whole chain is challenging but at the same time very profitable for companies. Therefore, this research aims to apply the lean methodology within the whole supply chain of a case company which is a manufacturer. Inventory is a critical item to address towards the goal of having lean supply chain. There are different supply chain inventory tactics and one of them is lean synchronization which has been selected in this study. It is proposed here to first achieve efficient safety stock and then make the inventory across the chain lean. According to the literature, there are many different methods and models for calculating and optimizing safety stock. An optimization safety stock model with the objective of total logistics costs minimization has been developed in this study. The challenge that was faced was making the optimization safety stock model applicable not only to one portion of the supply chain but also across it; and consequently, finding not only the optimal level of safety stock but also its location.

There are different metrics for measuring and assessing supply chain performance. Integrating them is a challenging task. In this study, the most appropriate metrics for this purpose have been introduced and a simulation safety stock model has been developed on their basis.

Chapter Three

Model Formulation and Solution Approach

In this chapter, we present details of the research problem at hand and develop a mathematical model formulation for applying a safety stock cost minimization model to a manufacturer case company. In addition, a simulation model for the same purpose of optimizing level and location of safety stock is provided. After that, the efficient inventory model with the input of optimized safety stock will be explained for the case company. First, we discuss the case company and its characteristics.

3.1 Case study characteristics

The company under study, which we will hereinafter refer to as ABC for the purpose of confidentiality, is a manufacturer in the aerospace industry. The company is characterized by high demand variability and long lead time, among others. ABC is a multi-stage manufacturer. Tiers of suppliers, procurement, manufacturing, final assembly, and customers (internal and external) are different nodes of ABC's supply chain. The downstream nodes are the upstream nodes' customers, and the replenishment lead time of customer nodes is the order waiting time provided by their upstream nodes. In addition, ABC has a generally structured multi-stage system and there is no restriction with respect to the number of predecessors and successors of any node. Such multi-stage systems focus considerable attention on setting and positioning safety stock (Jonathan and Omosigho, 2003). ABC has two different manufacturing plants (MFs). The procurement department of the company is responsible for procuring the raw materials or semi-finished parts through suppliers to manufacturing plants or even supplying parts from one manufacturing plant to another (inter plants transfers). The term "supplier" in the model could be the representative of the external supplier or internal manufacturing entity. It should be noted that procurement's location can be different from manufacturing ones. Finished parts from manufacturing entities have two internal customers that pull their outputs; they are Assembly (ASSY) and Aftermarket (AFM). These two latter entities are the last stages of the internal chain of the company just before the end customer. There are also some external supplied finished parts required for Assembly and Aftermarket that the procurement department supplies. The Assembly entity has different finished product families with their own specifications. Therefore, if availability of parts (right parts at right time) can be assured for the internal customers, on-time delivery performance to the end customer will be assured as well. This availability should be guaranteed through safety stock, but the optimum safety stock level and location should also minimize logistics costs.

3.2 Case company's inventory and safety stock problems

Nowadays, companies are becoming more and more interested in being lean to maintain competitiveness in the market. There are different areas within a company that could be improved towards making the company and its whole chain lean and leveraging from its benefits. One of the most important among these areas is the "inventory" of the company, which must be efficient according to lean principles. There are a number of different inventory drivers and safety stock is one of them. Indeed, the case company tries to manage the inventory across its supply chain efficiently, and towards this goal, efficient levels and locations of safety stock have become more and more highlighted as a prerequisite condition.

Therefore, doing research on efficient management of safety stock and inventory and their models and also applying them in the case company are the purposes of this study. Cost minimization has been selected as the objective of the safety stock efficient model according to the desire of the case company's management. Since improving inventory turns is the goal of the company as a whole, it has been selected as the objective of the efficient inventory model.

Optimizing the safety stock is not only about determining its level but also about its location within a supply chain. Then, by having efficient safety stock as a bucket of inventory, a company can improve its inventory turns.

In order to apply the safety stock and inventory models in a real world case, preparing the most appropriate input data is critical to obtain the desired results. Data was collected through many different databases, reports, and also the company's SAP system, as well as with the help of operational and strategic support personnel at ABC. The databases and metrics used will be discussed in more detail in the next sections.

3.3 Model formulation

As discussed before, ABC's goal was to minimize its logistics costs by having efficient safety stock as it is the most appropriate cost to be targeted in today's competitive market. The optimization safety stock model is presented through different possible value streams of each finished product family of the company to result in the optimum level of safety stock with its optimum location in the stream. Each of these value streams can have different combinations of the chain's contributors before the end customer. In order to limit the number of stages and for simplification, only the last two stages of those value streams that have more than two nodes before the internal customer stage are selected. Therefore, all the previous stages and their connections are being excluded and their performances are being captured only through the input of the latest second stage. The other reason for this limitation is the difficulty in defining the shortage costs in upstream stages of the chain due to lack of visibility and control. Furthermore, the objective of the model is cost minimization, and the upstream stages' contributions towards cost are significantly less than the downstream stages, thus this simplifying assumption should have a negligible effect on overall results. A sample is presented in Section 4.1 (Computational Results) that goes beyond this limitation just to show the applicability of the model for the whole chain from end to end.

In this study the assumption of not having materials stock out, which has already been considered (Aleotti Maia and Qassim, 1998) is being relaxed and shortage cost has been assigned to this. Shortage cost, overage cost, and delivery performances (percentage of product availability) are the inputs of the model. Different combinations of raw materials (semi-finished parts) and finished parts are considered as indices in the model based on the selected value streams.

3.4 Model notations

For all value streams, the notations of the model are as follows:

Index sets

i Raw material/ semi-finished part

p Finished part

u Customer (ASSY, AFM)

Variables

K_i Delivery performance of procurement to manufacturing

K_p Delivery performance of manufacturing or procurement to customers

Parameters[1]

P_i Supplier delivery performance to procurement
(If supplier is a manufacturing plant, then P_i would be manufacturing performance for semi-finished part)

P_p Manufacturing performance for finished part
(Ratio between on time manufactured and planned manufacture of finished part)

C_s Cost of shortage

C_o Cost of overage

x_i Raw material/semi-finished part safety stock

x_p Finished part safety stock

q_i Raw material/semi-finished part quantity ordered

q_p Finished part quantity ordered

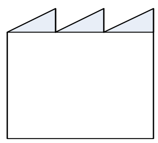
q^* On-time delivered quantity of raw material/ semi-finished part or finished part

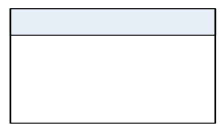
---

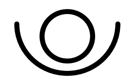
[1] It should be noted that in parameters "p" is used for only those finished parts that are manufactured in ABC. For those finished parts that are procured directly through suppliers, index "i" is used.

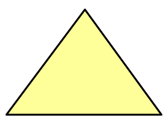
3.5 Safety stock model formulation

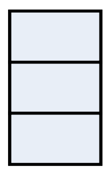
Figures 3.1 to 3.3 present variables and parameters in possible value streams for supplying a part to the customer in the case company. The symbols used in the value streams are explained as follows.

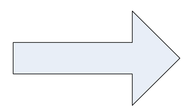

Customer /Supplier


Distribution/Process Box


Operator


Inventory


Safety Stock


Shipment Arrow

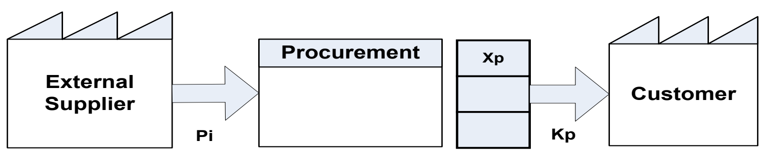


Figure 3.1 Variables and parameters in value stream

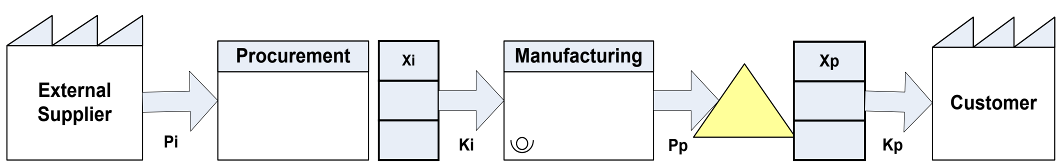


Figure 3.2 Variables and parameters in value stream

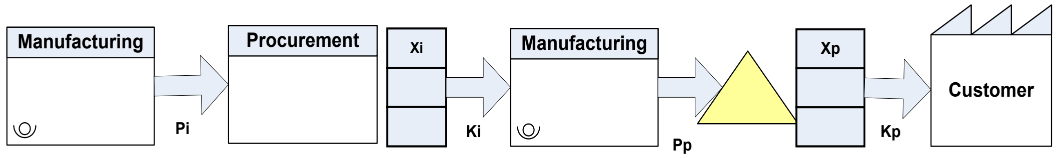


Figure 3.3 Variables and parameters in value stream

K_i is the summation of the availability percentage of raw material/semi-finished part for manufacturing through procurement based on the absolute suppliers' performances (P_i) and the availability percentage of procurement's safety stock for that part (x_i/q_i). Indeed, procurement can deliver whatever quantities they received on time through suppliers plus their safety stock to manufacturing. K_p is the summation of the availability percentage of the finished part which is dependent on the manufacturing performance (P_p) and also their previous stages' performances (K_i) and the availability percentage of manufacturing's safety stock for that part (x_p/q_p). Likewise, manufacturing can deliver whatever quantities of finished parts they can produce on time which is also dependent on the deliveries of their previous stages in the chain plus their own safety stock quantities to their customers (ASSY and AFM).

The related formulas of K_i and K_p are as (1) and (2):

$$K_i = P_i + x_i / q_i \qquad (1)$$

$$K_p = P_p \times K_i + x_p / q_p \qquad (2)$$

In the cases that the finished part is directly procured through the external supplier for the customers, the K_p formula will be equal to (1).

P_i and P_p are calculated as average numbers based on historical data from the last year. A report called the First Filled Rate (FFR) is used for calculation of these parameters. This report is used to present the availability of the right part at the time that is required. The FFR result takes into account the total on hand stock in its calculation which does include safety stock as well. It should be noted that P_i and P_p should be the absolute delivery performance of supplier and manufacturing without the contribution of the safety stock that may be used during the last year. Therefore, the safety stock has been excluded from the FFR report for this purpose. In addition, when there are two stages in the selected value stream, the FFR report also includes the contribution of the second to last stage's performance in its results for calculating the last stage's performance which is manufacturing. Therefore, this must also be excluded. P_p is the manufacturing performance without taking into account the stockout of raw materials (Aleotti Maia and Qassim, 1998). Hence, to calculate the required absolute value of P_p from FFR, three other parameters should be defined. The first one is K'_p which is the exact number extracted through FFR, the other one is P'_p which is the FFR's result excluding safety stock contribution. And the third one is K'_i which is the historical previous stage's delivery performance; by dividing this by P'_p the absolute manufacturing performance is measured ($P_p=P'_p/K'_i$). There is no direct report for tracking absolute manufacturing performance in the case company. Table 3.1 is a snapshot of a sample FFR and presents the formulas used to eliminate the safety stock from its calculation. As shown in the table, in the 12th week of 2010, the FFR report gives K'_p=100% as the delivery performance of manufacturing to its customer because it takes into account the 300 pieces of safety stock for meeting the past and current requirements; however, safety stock must be excluded through this calculation and P'_p becomes 18%. The next step for calculating the absolute manufacturing performance would be the elimination of the effect of the previous stage's performance (K'_i). Table 3.1 provides a sample calculation of P_p. The same steps would be required for calculation of P_i, but, it should be mentioned that if P_i is related to a supplier which is the first stage of the value stream, there would be no need to exclude the previous stage's performance.

Table 3.1 First Fill Rate Report Sample

Part Code	Entity	Calendar Week	Stock	Required Past	Required Current	% Met Global (K'p)	Theoretical Safety Stock	Safety Stock On-Hand	q*	P'p
AF1	MF	11.2010	2100	500	500	100	0	0	500	100%
AF1	MF	12.2010	1100	700	560	100	300	300	100	17.85%

* Shaded sections are used to make the FFR report applicable.
* Theoretical safety stock based on historical data for the required period.
* Safety Stock On-Hand = Max (0, Min (Stock - Required Past, Theoretical Safety Stock))
* q* = Max(0 ,Min (Stock - Required Past - Safety Stock On Hand, Required Current))
* P'_p = (q*/Required Current)×100

About the calculation of P_i in FFR, it should be noted that if the supplier delivers a part on time with the right quality, but defects occur during transportation from procurement to manufacturing or customer, although the delivery performance of the supplier is 100%, P_i will be 0% since the part is not available for use. Therefore, P_i can also be called "part availability" instead of supplier delivery performance.

It is worth mentioning here that ABC has three different strategies for managing its inventory. It applies a two-bin kanban system for the parts with low costs. The company is moving towards excellence and applying a pull system for managing the inventory of those parts that have high cost with high volume; but this system is not applicable for all parts due to the complexity and lack of required conditions such as having suppliers with delivery performance of higher than 80% and with a supermarket of finished goods, having parts with a robust process and steady volume, among others. Therefore, its inventory strategy for the rest of the parts with high cost and low volume is an MRP system. Based on this, a safety stock strategy is required for this latter category of parts. To calculate q_i and q_p, we need to understand the *risk period*, which consists of a review period and replenishment lead time (Tempelmeir, 2006). The review period is the basis on which the company updates its data. As a result, if a company reviews its data once a week, its review period would be one week. Of course this review period has an effect on the duration that the company should wait to receive its order through the supplier to be replenished. In the case company, the data is updated daily; therefore, there is no need to define the review period. Consequently for parts managed by the MRP system, quantities within the replenishment lead time have found as the most appropriate definition for q_i and q_p to result in the proper level of safety stock for the company through the model. In essence, if changes happen in demand within this period (replenishment lead time), we cannot count on the suppliers' support 100% of the time. Safety stock is required for coverage of this variability. The first step for its calculation would be identifying the planned order quantity of each specific part (raw/semi or finished part) per week according to its planning parameters which it itself is related to ordering policies. Some of the examples of planning parameters in this regard are Lot for Lot, Weekly Batch, 2 Weeks Batch, and Fixed Order Quantity, among others. The second step would be the calculation of the average weekly forecast demand of that specific part for the next year. After that, the division of the planned order quantity and average weekly demand would result in the replenishment lead time in weeks. When changes happen in the supply chain such as changes in the demand or capacity ration, entrance of new competitors, introduction of a new product, or retirement of a matured one, the safety stock required for the supply chain must be re-evaluated (Jung et al., 2008). ABC has decided to run the model and update it every quarter, therefore, the weekly demand of the next quarter would be merged based on the calculated replenishment lead time. And finally, the maximum quantity of this combination will be selected as q_i/q_p in order to allow the safety stock strategy to support the *worst case*.

One of the advantages of this method of calculating q_i and q_p is making the market variability involved by taking into account the forecast demand. It should be mentioned that the planned order quantity for a manufacturing part should always be calculated through its demand only in the plant in which it is being manufactured because the part will be replenished based on the ordering policy in that plant. On the other hand, in the case that a raw material has more than one customer (MF and AFM), calculation of q_i required by manufacturing through weekly demand seen in procurement (entity that receives part through supplier) is not correct because procurement sees the demand of both customers' mix. Therefore, the respective q_i must be calculated through the part's parameters (planned order and weekly demand) all in the manufacturing plant in which it is going to be used.

Shortage costs (costs of safety stock violation) have different definitions for raw materials (semi-finished parts) and finished parts as they are located in different stages within the chain and their shortages have different effects on the system. The shortage cost of the raw material (semi-finished part) is the summation of the expediting cost on the supplier, expediting cost on transportation, and overtime of the manufacturing section. On the other hand, shortage of the finished part which is required by Assembly causes disruptions and stock not pulled for all the other parts related to that finished part in different locations of the supply chain. In addition, shortage of the finished part causes the finished assembled product to be held up unreleased. Therefore, the shortage cost is defined as follows:

C_{sp} = (Standard cost of the finished assembled product* average days of holding finished assembled product due to the shortage of the specific finished part during last year*0.1)/365

The coefficient of 10% in the above formula is the annual interest rate that company could receive by putting this amount of money in the bank, although the company currently has this as inventory buckets instead of cash.

The cost of shortage of the finished part required by Aftermarket is defined as the profit that the company will lose by not having the part ready to deliver on time to the customer, which is the direct cost. Besides that, there are many intangible effects of this shortage that are called indirect costs and are difficult to gauge accurately (Graves and Rinooy Kan, 1993). One of them is loss of customers' goodwill that may turn them to other competitors in the future. On the other hand, at the time of shortage of a specific part, the Aftermarket department may rent out another more expensive part instead of the required one to the customer until it arrives. Therefore, the shortage cost of these parts is defined as four times of the standard cost (Stnd.Cost) of the finished part.

The cost of overage is defined as the interest that the company is losing by holding inventory instead of having it in cash. Hence, it is the multiplication of standard cost of the part and the annual interest rate (10%).

As can be seen through the formulas and definitions, a period of one year has been selected for historical data collection. As the factors (such as shortage cost and delivery performances) that are gathered within this time frame are critical to make an appropriate decision about the level and location of safety stock, one year has been selected in order to have a sufficient window view. Some samples of value streams associated with their models' formulas are presented below.

Value stream I shown in Figure 3.4 consists of one raw material/semi-finished part used to make one finished part which has two customers, ASSY and AFM.

The corresponding objective function and constraints for value stream 1 are presented in (3).

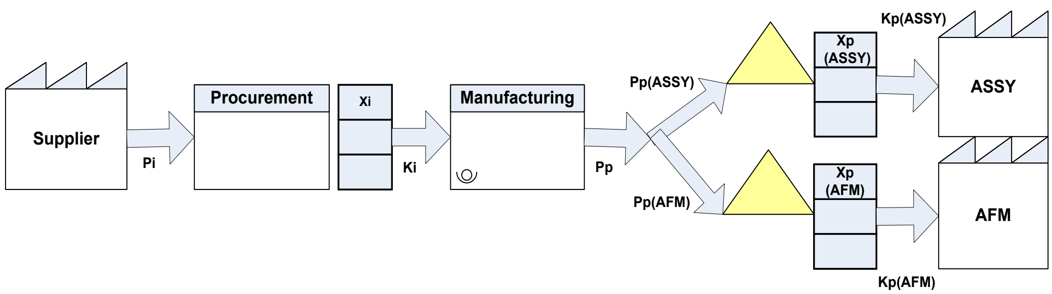


Figure 3.4 Value stream I

$$MinC = C_{si}q_i(1-P_i)+C_{oi}q_i(K_i-P_i)+\sum_{u=1}^{2} C_{spu}q_{pu}(1-K_{pu})$$
$$+\sum_{u=1}^{2} C_{opu}q_{pu}(K_{pu}-(P_{pu}\times K_i))$$

$$\begin{aligned} &SubjectTo: \\ &K_i \le 1 && i=1 \\ &K_i \ge P_i && i=1 \\ &K_{pu} \le 1, && p=1,\ u=1,2 \\ &K_{pu} \ge P_{pu}\times K_i, && i=1, p=1, u=1,2 \end{aligned} \quad (3)$$

The above objective function includes the shortage cost and overage cost of the raw material, shortage cost and overage cost of the finished part for both customers of ASSY and AFM. The constraints are about the boundaries for the delivery performances of the raw material (semi-finished part) and the finished part. The first and third constraints are about the upper boundaries of K_i and K_{pu} which are 100%. The second constraint shows that the delivery performance of procurement to manufacturing is equal to or greater than the supplier delivery performance to procurement due to having safety stock. The fourth constraint shows that the delivery performance of manufacturing to customer is equal or greater than the multiplication of the manufacturing performance and the delivery performance of procurement to manufacturing. Again safety stock makes K_{pu} greater than the right side of the equation.

If for this case, there were two different kinds of finished parts but again in demand with both customers, then there should be a summation on both indices of finished part (p) and customer (u) in the objective function:

$$
\begin{aligned}
MinC = {} & C_{si} q_i (1 - P_i) + C_{oi} q_i (K_i - P_i) \\
& + \sum_{p=1}^{2} \sum_{u=1}^{2} C_{spu} q_{pu} (1 - K_{pu}) \\
& + \sum_{p=1}^{2} \sum_{u=1}^{2} C_{opu} q_{pu} (K_{pu} - (P_{pu} \times K_i))
\end{aligned}
$$

$$
\begin{aligned}
& SubjectTo: \\
& K_i \le 1 && i = 1 \\
& K_i \ge P_i && i = 1 \\
& K_{pu} \le 1, && u, p = 1, 2 \\
& K_{pu} \ge P_{pu} \times K_i, && i = 1,\ u, p = 1, 2
\end{aligned}
\tag{4}
$$

Therefore, there would be summation on both indices of customer and product for calculating the shortage and overage cost of the finished parts.

The mathematical proof of the last constraint of (4) (with one customer) when there are two finished parts which require a common raw material is presented in Appendix A that can be extended.

In value stream II which is shown in Figure 3.5, two raw materials/semi-finished parts are used to make one finished part which has two customers, ASSY and AFM. The corresponding model is also presented by (5).

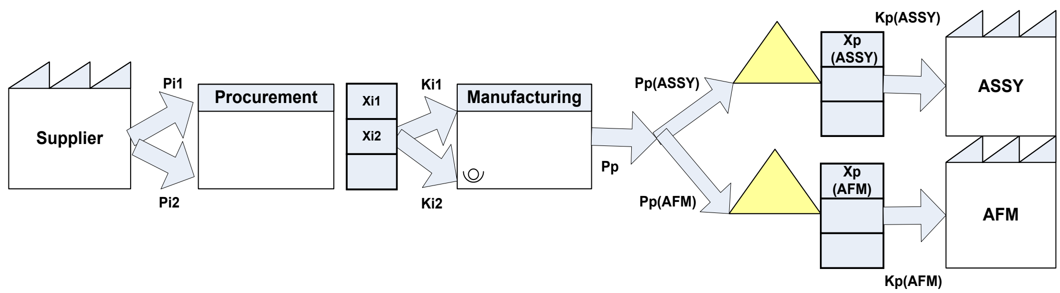


Figure 3.5 Value stream II

$$
\begin{aligned}
MinC = & \sum_{i=1}^{2} C_{si} q_i (1-P_i) + \sum_{i=1}^{2} C_{oi} q_i (K_i - P_i) \\
& + \sum_{u=1}^{2} C_{spu} q_{pu} (1-K_{pu}) \\
& + \sum_{u=1}^{2} C_{opu} q_{pu} (K_{pu} - (P_{pu} \prod_{i=1}^{2} K_i))
\end{aligned}
$$

$$
\begin{aligned}
& SubjectTo: \\
& K_i \le 1, \quad i=1,2 \\
& K_i \ge P_i, \quad i=1,2 \\
& K_{pu} \le 1, \quad p=1,\ u=1,2 \\
& K_{pu} \ge P_{pu} \prod_{i=1}^{2} K_i, \quad p=1,\ i,u=1,2 \qquad (5)
\end{aligned}
$$

Hence, as there is more than one raw material in the value stream II, there is a summation on the raw material indices as well for calculating their costs.

As before, if there were two different finished parts for the same situation, the model would be changed as (6):

$$
\begin{aligned}
MinC = & \sum_{i=1}^{2} C_{si} q_i (1 - P_i) + \sum_{i=1}^{2} C_{oi} q_i (K_i - P_i) \\
& + \sum_{p=1}^{2} \sum_{u=1}^{2} C_{spu} q_{pu} (1 - K_{pu}) \\
& + \sum_{p=1}^{2} \sum_{u=1}^{2} C_{opu} q_{pu} (K_{pu} - (P_{pu} \prod_{i=1}^{2} K_i))
\end{aligned}
$$

$$
\begin{aligned}
& SubjectTo: \\
& K_i \leq 1, \quad i = 1,2 \\
& K_i \geq P_i, \quad i = 1,2 \\
& K_{pu} \leq 1, \quad p,u = 1,2 \\
& K_{pu} \geq P_{pu} \prod_{i=1}^{2} K_i, \quad i,p,u = 1,2
\end{aligned} \tag{6}
$$

Therefore, as shown in equation (6), there is a summation on all indices of the raw materials, finished parts, and customer as there is more than one of each.

As can be seen through the constraints of the model, the company's objective is to have 100% delivery performances. Therefore, the upper boundaries of both stages are assigned to 1 in order to not to allow the model to impose a shortage to the system. Of course, these upper bounds could be less than 1 based on the service level goals in different cases.

By this definition of the model, cost factors would be the indicators for the location of the safety stock and its level would be identified based on the boundaries of the delivery performances.

This optimization model will be linear if there is only one raw material/semi-finished part and optimum point with minimum cost will happen only in one of the four boundaries. Based on this, we assume the optimization model as (7) with only one customer for finished part:

$$MinC = C_{si}q_i(1-P_i)+C_{oi}q_i(K_i-P_i)+$$
$$C_{spu}q_{pu}(1-K_{pu})+C_{opu}q_{pu}(K_{pu}-(P_{pu}\times K_i))$$

$$\begin{aligned}
&SubjectTo: & \\
&K_i \le 1 & i=1 \\
&K_i \ge P_i & i=1 \\
&K_{pu} \le 1 & p,u=1 \\
&K_{pu} \ge P_{pu}\times K_i & i,p,u=1
\end{aligned} \tag{7}$$

Varying the location of the safety stock based on the optimum point in two sample cases of the linear model in (7) are shown with the following feasible regions in Figures 3.6 to 3.9. In addition, Table 3.2 presents the comparison between the costs in each of the cases and also the recommended location of the model for the safety stock. In this comparison, it is assumed that q_i and q_p are equal.

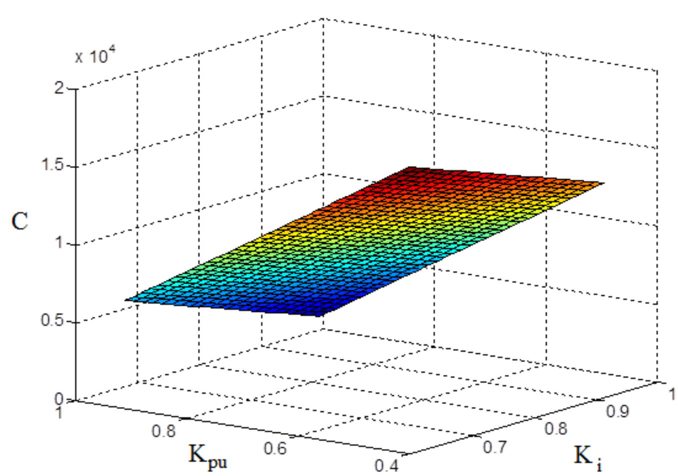


Figure 3.6 Location of safety stock - Case 1

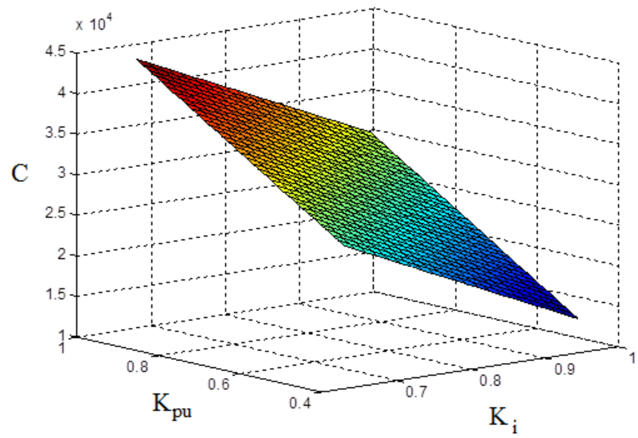


Figure 3.7 Location of safety stock - Case 2

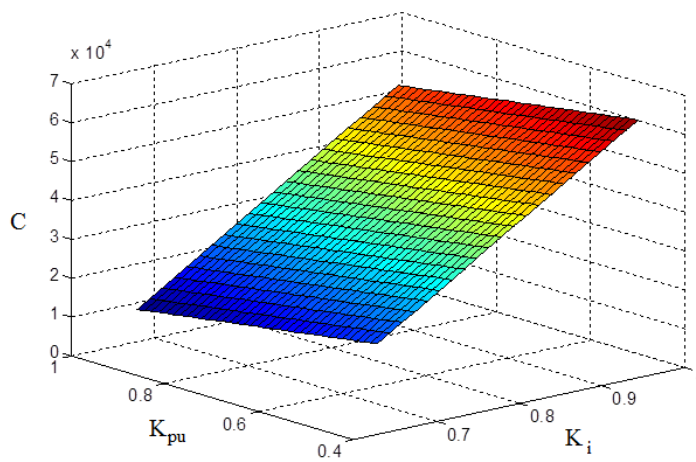


Figure 3.8 Location of safety stock - Case 3

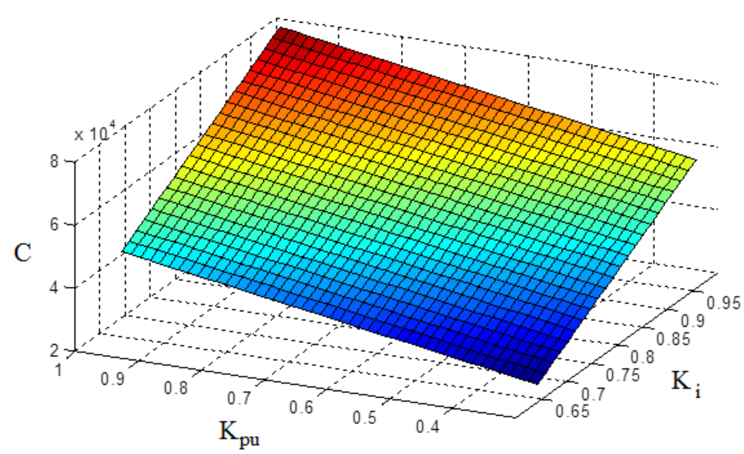


Figure 3.9 Location of safety stock - Case 4

Table 3.2 Costs comparison and safety stock locations

Case	Costs Comparison	Safety Stock for Raw Material	Safety Stock for Finished Part
1	Csp>Csi>Cop>Coi	Yes	Yes
2	Cop>Csp>Csi>Cos	Yes	No
3	Coi>Csp>Cop>Csi	No	Yes
4	Cop>Coi>Csp>Csi	No	No

In order to make the results of the model more effective for the company, one of the most problematic finished product families of the Assembly was selected, and value streams of its finished parts that were going to be assembled were reviewed with the model. As each of the selected final product families could have 100 different value streams in the company, it was decided to apply the optimization model only for those value streams that end with finished parts that were consistently in shortage reported during the last year in order to limit samples. Value streams of these pacer parts vary (pacer parts are those for which their shortage would cause a finished product to be held and not released). Some of them could have only the supplier stage before the assembly and some others could be very long. As discussed before, these long value streams were limited by taking into account only parts of level 1 and 2 of its finished product's bill of materials (BOM).

3.6 Case company's safety stock simulation model

Besides developing an optimization model, a simulation model is also provided to find the most appropriate level and also location of safety stock for the case company under study. It should be noted that all data that are presented in the tables of this section are the masked data due to confidentiality.

As a first step, metrics used at the company for measuring the performances of its supply chain were collected to help build the simulation model. The first one is called On-Time Delivery (OTD) which shows the delivery performance of the supplier (internal or external) to its customer(s) (internal or external). However, this metric is not the best one for three main reasons. The first reason is that if the company, due to the unexpected changes in demand, expedites a purchase order (PO) and asks the supplier to send the parts of the respective PO earlier and the supplier does not accept it, then the due date of purchase order will not change in the system and OTD will show 100% delivery for this case to the supplier, even though the company was in shortage for that whole period. The second reason is that the OTD does not consider quality problems. Indeed, availability of parts that are important for the company depends not only on receiving them on time but also on the right quality. Therefore, if the company receives the parts of a specific PO by its due date, the OTD will report 100% regardless of the possibility for the part to have quality problem which will be found within the inspection process. The last reason is related to the incorporation of safety stock in OTD's calculation for delivery performances that does not result in the pure delivery performances.

Therefore, another metric called First Fill Rate (FFR) which has been already defined in the optimization safety stock model will be used in our simulation model. It should be noted that OTD and FFR are calculated based on the last six months' records. FFR would normally be the average of this record, but OTD is calculated as the "weighted average" as it is being reported with the percentage aligned with deliveries.

The third metric is the Length of Lateness which represents how many days a specific part is delivered late to its customer within the supply chain. Length of Lateness is equal to Posting Date minus Statistical Date.

The fourth metric is the Safety Stock Coverage (in weeks) which is calculated by dividing each part's safety stock's quantity into its weekly requirements (demand).

And finally the last metric is the information extracted from the quality report which reports the parts that have quality issues and create the bucket called quality lot. This report includes quality issue creation date, quality issue completion date, and quantity of parts with quality issues.

In order to develop the desired simulation safety stock model, we have to find the distribution of safety stock within the supply chain to determine if it is located properly with the support of the defined metrics. Hence, as a first step, a matrix has been developed as shown in Table 3.3. This table includes different finished products of the company in the row and the contributors of the supply chain in the column and the value of the safety stock related to each combination of the product and supply chain contributor. Table 3.4 shows this matrix more specifically for the case under study.

Table 3.3 Safety stock distribution pivot table template

	Finished Products →
Supply Chain Contributors ↓	Safety Stock Values ($)

Table 3.4 Case company's safety stock distribution pivot table

Sum of SS Value Split					
Supply Chain Contributors	AB	AE	AF	ACD	AG
Procurement	$107,170	$105,870	$726,680	$290,340	$125,780
Manufacturing	$566,120	$348,420	$235,596	$65,072	$91,400
Assembly	$42,170	$9,194	$7,800	$17,500	$14,012
Grand Total	$715,460	$463,484	$970,076	$372,912	$231,192
Sales Volume ($M)	$25	$40	$105	$27	$26

The total value of safety stock of each finished product will be compared with its total value of sales in the past (for example last year) through this matrix. This comparison will give us an idea of whether the current value of safety stock for each finished product is aligned with its sales value or not. It may be even determined that we are keeping the same value of safety stock for two different finished products while the sales value of one was even twice of the other one. For example, although the volume of finished product AB is really lower than the volume of AF, still the value of its safety stock ($715,460) is somehow equal to the safety stock value of AF ($970,076). On the other hand, it is shown that manufacturing makes the biggest portion of AB's safety stock value ($566,120). Therefore, this pivot table (Table 3.4) will give us a direction for more investigation.

The next matrix that is required to help find the most appropriate location of safety stock would be a table with the combination of OTD and Length of Lateness , as shown in Table 3.5.

Table 3.5 OTD and Length of Lateness Matrix for Finished Product AB

Sum of SSValue Split						
	Length of Lateness Classification					
Supply Chain Contributors	OTD Classification	<=0	<=14	>14	No Delivery	Grand Total
Procurement	100%	$18,370	0	0	0	$18,370
	80-90%	0	$22,648	0	0	$22,648
	<80%	0	$36,114	$26,519	0	$62,633
	No Delivery	0	0	0	$3,519	$3,519
Procurement Total		0	0	0	0	$107,170
Manufacturing	100%	0	0	$72,778	0	$72,778
	80-90%	$22,394	0	$174,819	0	$197,213
	<80%	0	$25,884	270245	0	$296,129
	No Delivery	0	0	0	0	$0
Manufacturing Total		0	0	0	0	$566,120
Assembly	100%	$1,441	0	0	0	$1,441
	80-90%	0	$29,749	0	0	$29,749
	<80%	0	$3,109	$7,679	0	$10,788
	No Delivery	0	0	0	$192	$192
Assembly Total		0	0	0	0	$42,170

OTD=100%
No Deliveries within the last 6 months
Low OTD with long lateness

As shown in the above table, some ranges are selected for OTD and also for Length of Lateness in order to limit the decision areas. OTD has been classified as on-time (OTD=100%), between 80% to 90%, less than 80%, and “No Delivery”. Length of Lateness has been categorized as on-time or early deliveries (<=0), late deliveries for less than or equal to 14 days, late deliveries for greater than 14 days, and “No Deliveries”. In fact, at first glance, it may be concluded that parts located in the green area are good opportunities for safety stock reduction. However, it is clear that there should be other indicators to make the final decision in this regard. The required indicators are FFR, Safety Stock Coverage, and Quality Report. In what follows, we discuss the table according to the colored areas.

Discussion of green area:

First of all, FFR is checked. If it is 100% then quality report will be checked for further investigation. If the part does not exist in the quality report, safety stock will be removed. But, if the part has had quality problems, then the days that the part stayed in the quality lot will be compared to the coverage days of the current level of safety stock. If, the coverage and days of quality report are equal, there would be no change for safety stock. If, coverage is less than the quality report days, then safety stock should be increased; otherwise, reduction in safety stock is required.

If FFR is not 100%, again quality report will be checked. If the part does not exist in the quality report, more investigation required to find out the reason of not having the FFR of 100%. On the other hand, if the part exists in the quality report, the same comparison as above for the days of coverage and days of quality problem will be done. If the coverage and days of quality are equal, we do not need to change the current level of safety stock; meanwhile, investigation is required as FFR could not be 100%. One of the reasons for this could be that it is not able to fulfill the current safety stock level. If the part has not had quality issues, and the current coverage of safety stock is greater than the quality report days, it should be find out that why FFR is not still 100%, although the kept level of safety stock is even greater than required. If the coverage is less than the quality days, safety stock level needed to be increased. This discussion can be found in the following flowchart (Figure 3.10).

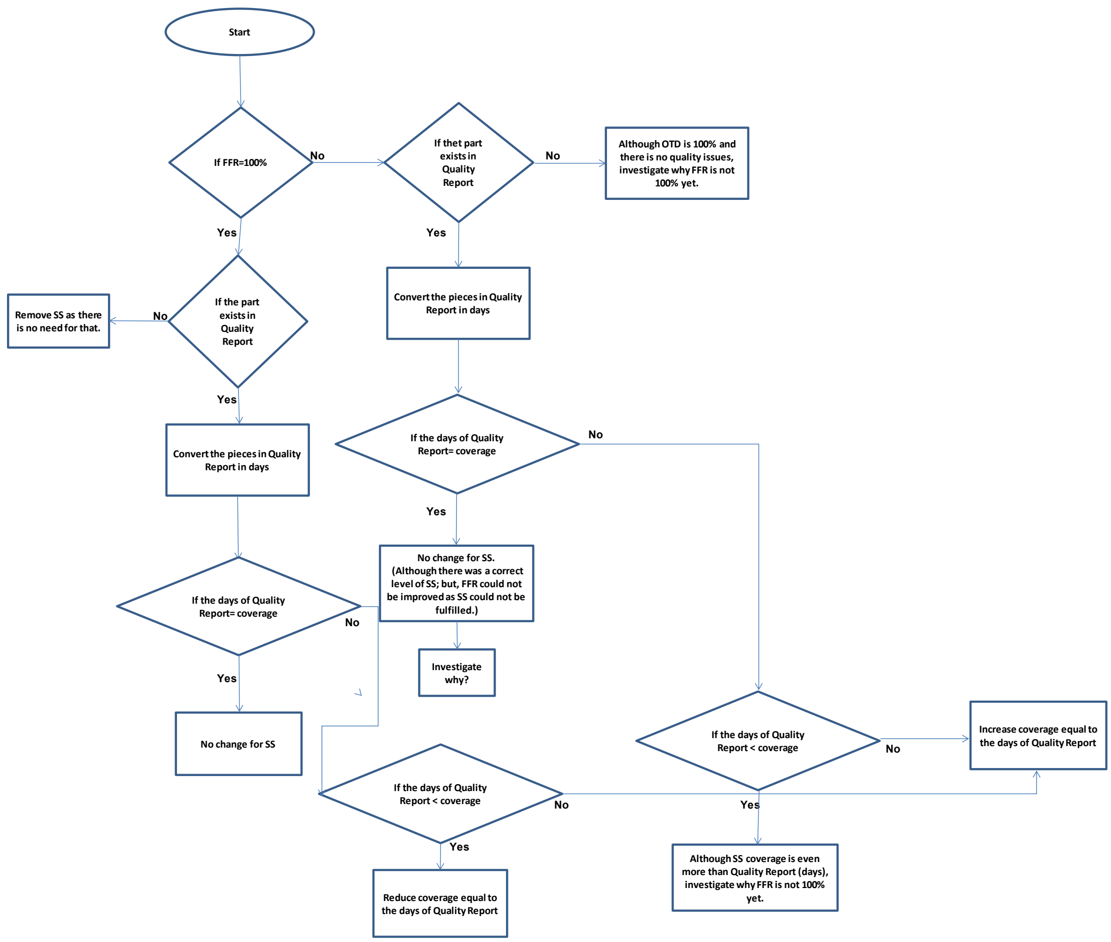


Figure 3.10 Green area flowchart

Discussion of yellow area:

This area could be related to the parts that are delivered in low frequencies but in big batches. Therefore, it cannot be concluded right away that safety stock be removed. Indeed, we need to make sure that whenever these parts arrive they do not have quality issues. Then, their safety stock can be removed; otherwise, removal of their safety stock will cause the company to be in shortage.

Discussion of red area:

As it is shown in Figure 3.11, initially it will be checked whether the part exists in the quality report or not. If yes, then FFR and OTD will be compared with each other. If FFR is less than OTD, we need to make sure that the current coverage covers the late delivery and also quality issues. If FFR is greater than the OTD, then it should be checked if FFR is 100% or not, and after that safety stock coverage should be compared with the quality report (days) plus lateness.

On the other hand, if the part does not exist in the quality report and FFR is less than OTD, we need to investigate the reason as there is no variability due to quality issues in this case and level of safety stock should be only equal to the lateness in the delivery. But, if FFR is greater than OTD, it should be checked whether FFR is 100% or not, and then safety stock coverage should be compared with lateness.

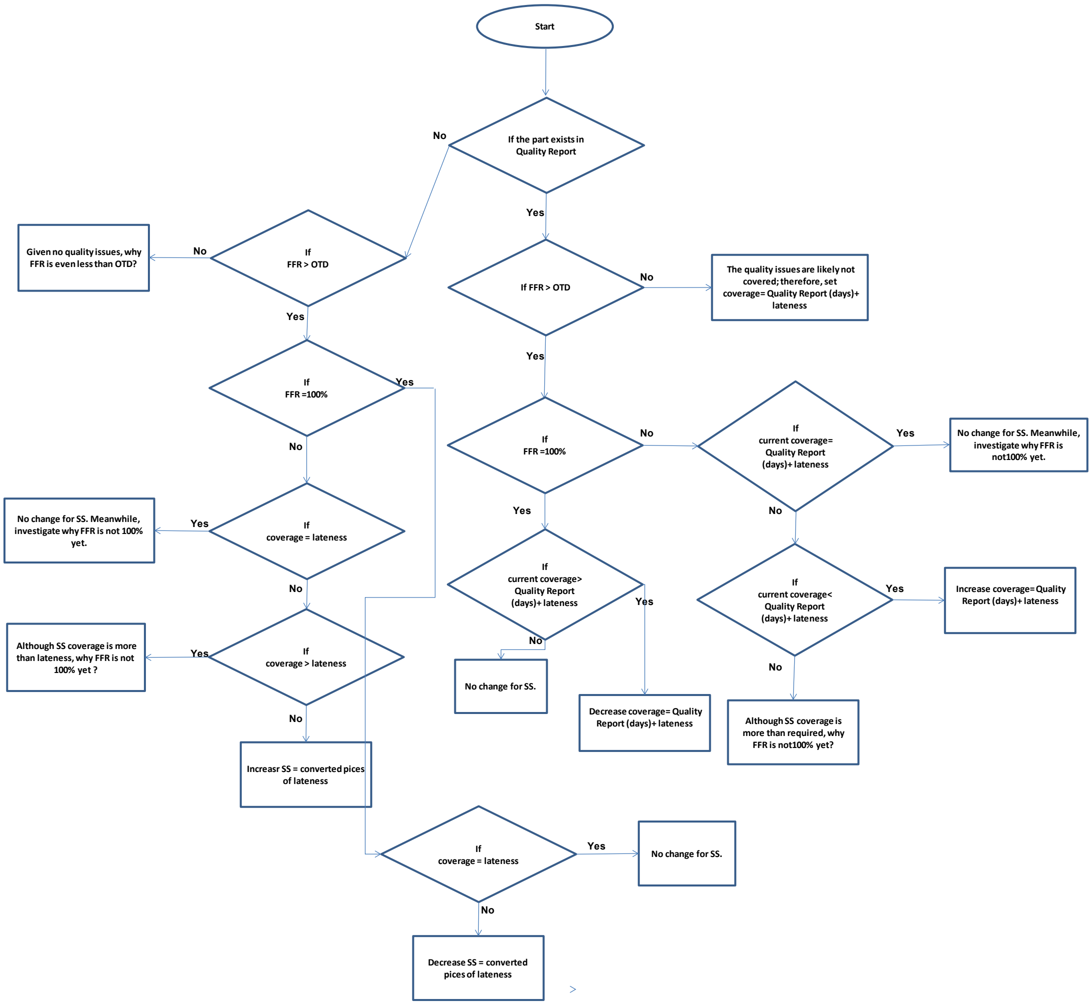


Figure 3.11 Red area flowchart

For simplification, the summary of the above processes is as follows.

Case 1)

If OTD ≠ 100%
and
If FFR <=100% and >OTD

} then, safety stock has been helpful

but make sure that:

-If there was quality issue ⟹ Coverage = Lateness + Quality Report (days)
-If there was no quality issue ⟹ Coverage = Lateness

Case 2)

If OTD $\neq$ 100%
and
If FFR $\neq$ 100% and < OTD

then, check:

- If there was quality issue $\Longrightarrow$ Coverage = Lateness + Quality Report (days)
- If there was no quality issue $\Longrightarrow$ Coverage = Lateness

If the current level of safety stock is equal to or greater than the above values, it should be investigated for the reason of having FFR even less than OTD.

Case 3)

If OTD = 100%
and
FFR = 100%

then, check:

-If there was quality issue $\Longrightarrow$ Coverage = Quality Report (days)
-If there was no quality issue $\Longrightarrow$ Remove SS

Case 4)

OTD = 100%
and
FFR $\neq$ 100%

then, check:

- If there was quality issue $\Longrightarrow$ Coverage = Quality Report (days)
- If there was no quality issue $\Longrightarrow$ Investigate why with OTD of 100% and no quality issue, FFR is not still 100%?

To calculate the days that the part was in the quality lot to compare it with the coverage of safety stock, we need to provide the “Duration in Quality Lot (in days)” and “Frequency of appearing the part in Quality Report” within last year for each part. Then, the days related to the “Maximum” of the frequency would be representative of the days of being in the quality lot. If the maximum of the frequency is not unique, then the

"Maximum" of their duration days will be selected. Table 3.6 shows this information that was gathered at the company.

Table 3.6 Duration in Quality Lot (Days)

Part A							
	Duration in Quality Lot (in days)	1	2	3	4	5	6
	Frequency of appearing in the Quality Report	2	3	5	10	9	1

For the above sample, the maximum of the frequencies appearing in the quality report is "10"; therefore, its relevant duration which is "4" days will be selected to compare with the safety stock coverage. Regardless of the result of the quality report (whether it is "Ok" or "Scrap"), the part has not been available for the specific period. So the system needs to be protected with the safety stock equivalent of that time of unavailability. On the other hand, if the result of the quality report was "Ok", we will use that part released from quality report to replenish the safety stock that was already used. Two samples (Tables 3.7 and 3.8) highlight the necessity for ALL metrics to make a correct decision about the level and location of safety stock.

Table 3.7 Safety stock simulation model - sample 1

Part Code	Safety Stock (Pieces)	Demand/Week (Pieces)	SS Coverage (Days)	Length of Lateness (Days)	OTD%	FFR%
A	4	0.6	46	4	6%	100%

By only considering the above metrics for part A, we conclude that safety stock has been helpful; but as the coverage is greater than the length of lateness, it may be decided to reduce safety stock to make the coverage equal to the length of lateness. However, before moving towards reduction of safety stock, quality issues need to be considered. As FFR>

OTD, we are sure about safety stock being helpful for part availability. However, a buffer stock is needed if there exists any quality issues for this part. Therefore, the quality report must be checked and if there are no quality problems, it can be concluded that safety stock should be reduced only to compensate the weakness of the supplier to deliver and the company may survive even with less safety stock. On the other hand, if there is any record in the quality report that results in the part not being available, there is only a need to have safety stock equal to the length of lateness plus days of part the being in quality lot.

Table 3.8 Safety stock simulation model - sample 2

Part Code	Safety Stock (Pieces)	Demand/Week (Pieces)	SS Coverage (Days)	Length of Lateness (Days)	OTD%	FFR%
B	1	0.5	14	8	53%	94%

In the above sample, although safety stock kept with the coverage is greater than the length of lateness, FFR is not still 100%. Hence, we may conclude right away that there was a quality issue for this part. On the other hand, the reason that its FFR is not yet 100% could be due to having safety stock with the coverage which is less than the summation of length of lateness and the days that the part was in the quality lot. Thus, safety stock must be increased to become equal to the summation of the lateness and the days that part was not available due to quality issues.

3.7 Case company's efficient inventory (EI) model

One of the common questions for every business is "what is the optimal level of inventory to run the business?" One of the goals of the case company is increasing the inventory turns. On the other hand, reducing inventory may cause stockouts and loss of sales. Therefore, case company would like to determine the optimal level of inventory. It is known that best-in-class companies are 50-70% more likely than their peers to use supply chain inventory tactics (Aberdeen, 2004). Some examples are shown in Table 3.9, presenting companies who apply different tactics to make their inventory efficient.

Table 3.9 Efficient inventory tactics applied by different industries

Type	Company	Method	Result
Industrial Systems	**Carrier**	**Inventory Quality Ratio (IQR) Logic**	-Shortage have been reduced by as much as 75%. **-Sales have doubled with no increase in inventory levels.** -Normal MRP functioning Is improved due to a fewer database errors and omissions.
Design & Manufacture of gaming equipment	**International Game Technology (IGM)**	**Inventory Quality Ratio (IQR) Logic**	**20% Reduction in Inventory**
HP Imaging and Printing Group	High-Tech OEM	Multi-echelon optimization tool	slashed on-hand inventory by 20-30%
Dealer Network	Deere & Company	Multi-echelon optimization tool	reduced inventory in one of its divisions by the value of $4550 million

An inventory model called "Inventory Quality Ratio (IQR)" which is an inventory management technique is currently used widely in many industries. This model focuses on inventory dollars based on ABC classification and measures performances by segments. Inventory quality ration is calculated by dividing active inventory dollars to the total inventory dollars. Total inventory includes not only the active inventory, but also the "excess" (requirements divided by usage), "slow moving inventory" (the inventory which will not be used in 6 months), and "no moving inventory" (the inventory which will not be used in one year). The perfect inventory quality ratio is 100%. There are 3000 companies applying IQR nowadays and there are also some companies in the aerospace industry that are leveraging from it, such as Sikorsky Aircraft and Woodward Governor

(IQR International Improving Inventory Performance). The efficient inventory model selected for application in the case company is very similar to QR as they both are based on inventory dollar value objective, ABC classification, and part level results.

The efficient inventory model used in the case company is a simulation model that gives the company the capability to assess the benefits and risks of changes in the inventory strategies. It is based on the assumptions and hypotheses of different entities in the company. These entities are Procurement, Manufacturing (MF), Assembly (ASSY), and Aftermarket (AFM). The input of the model comes through the entities based on their objectives for their turns. These hypotheses and assumptions are validated by benchmarking to ensure their accuracy. Table 3.10 presents the company's entities with their assumptions for the efficient inventory model.

Table 3.10 Case companies' efficient inventory assumptions

Entity Name	**Assumptions**
Canadian Manufacturing	WIP→20 Turns FPS→35 Turns Safety Stock resulted through optimization tool
Aftermarket	4 week of cycle stock on all parts Safety Stock resulted through optimization tool
Procurement	1 Week of cycle stock on procurement parts Class A 2 Weeks of cycle stock on procurement parts Class B 4 Weeks of cycle stock on procurement parts Class C Safety Stock resulted through optimization tool
Assembly	35 Turns for A&T parts

Figure 3.12 shows the benchmark done through Supply Chain & Logistics Association Canada (SCL) of the year 2005 related to the raw material turns and its comparison with

the case company's turns. It can be seen that there is a good opportunity to improve this area at the case company in this regard.

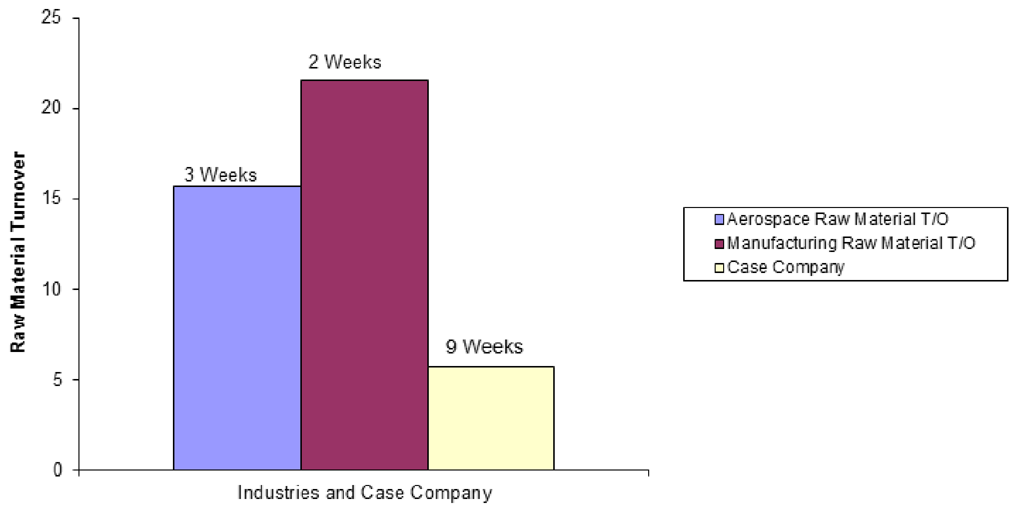


Figure 3.12 Raw material turns benchmark

The EI model was developed using Access 2003 with SQL coding and there are several tables and databases that are updated regularly as the inputs of the tool such as lead time, actual WIP, safety stock, weekly demand, among others. It is worth it to introduce and define different buckets of inventory of the case company. One of the buckets is called "Excess" which is the portion of inventory that will not be consumed in the next two years. The other bucket is related to the materials and inventory that have been bought through a new supplier for resourcing and will be kept without consumption until obtaining approval to do so. This bucket is called "Block Stock". Another bucket is called "QM lot" which includes the materials that require inspection. Some of them remain in the QM Lot due to problems such as quality problems. The other bucket of inventory is "OEM", which consists of materials that have been returned to the case company through the customers due to different problems. The other kind of inventory is called "SNP" or

"Stock Not Pulled" and it is the inventory that has not been consumed for any reason. Another bucket of inventory is "Cycle Stock", the inventory for which there is demand. Two other buckets of inventory which are completely known are WIP and safety stock. Among these buckets of inventory, only the last three (cycle stock, WIP, and safety stock) are desired in the efficient inventory model and the rest are recognized as non-efficient, and should be removed based on the "waste removal" rule of the lean philosophy. Table 3.11 is a sample of the output (masked data) of the EI model for the entity of manufacturing.

Table 3.11 Sample of EI result for manufacturing entity

Entity			
Manufacturing			
	Efficient Inventory ($M)		
		FPS	$18
		WIP	$32
		Safety Stock	$10
	Total Efficient Inventory ($M)		$60
	Actual Inventory ($M)		
		Excess	$2
		Block	$3
		QM	$3
		OEM	$1
		SNP	$9
		Safety Stock	$3
		Cycle Stock	$8
		WIP	$42
	Total Actual Inventory ($M)		$71

Entity	Total Efficient Inventory($M)	Total Actual Inventory($M)	Delta($M)
Manufacturing	$60.00	$71.00	-$11.00

Through the analysis done in the company, every entity of the case company holds some value of inventory in the non-efficient buckets such as Excess, Block, QM, and SNP rather than having them in the efficient buckets that create value for the company. Therefore, the EI model also leads to the appropriate management of inventory in the correct buckets in order to improve turns.

As mentioned before, due to the fact that the provided model in the case company is a simulation model, the assumptions and hypothesis used in the model should be validated more and more by benchmarking in the same industry. This EI model can be run weekly to analyze the performance of each entity towards efficient inventory.

By applying this EI model with the efficient safety stock input, the company is able to set the target for each entity's inventory (level and bucket) towards leanness and improve its turns at the same time. The simulation inventory model leads to reducing inventory, increasing turns, improving inventory performance by eliminating non-efficient buckets of inventory, and also improving cash flow.

Chapter Four

Results and Analysis

In this chapter, results of the safety stock optimization model applied to value stream samples of a finished product family are presented. Table 4.1 is the summary of these results. This table includes input factors to the model such as delivery performances (P_i,P_p), parts quantities (q_i, q_p), costs (C_s, C_o) along with parameters required to calculate them (K'_i, P'_p, K'_p, standard cost) for each value stream. This table also presents the old and new safety stock levels and total costs (for those cases that all required data were available) to compare the previous situation with the new one. All historical data presented in this table, as mentioned before in Section 3.5, are based on last year's records. In addition, recommendations of the model based on the analysis of real cases are explained. It should be mentioned that due to confidentiality, masked data are used in this section. The problem is solved using Lingo optimization software, version 11, on a PC platform with 2.2 GHZ and 2 GB RAM.

4.1 Computational results

In this section some value streams are presented in Table 4.1 and the results of applying the safety stock optimization model to these value streams are explained.

Table 4.1 Safety stock optimization computational results

Value Stream	Part Code	Entity	K'i	Pi	qi	P'p	Pp	qp	K'p	Stnd Cost	Cs	Co	Old xi	New xi	Old xp	New xp	Total Old Cost	Total New Cost
VS1	B	MF	0.65	0.57	1400					$40	$2	$4	0 & 500	602			$497,732	$15,116
VS1	AB	ASSY				0.40	0.62	1100	0.53	$120	$500	$12			1 & 8	429		
VS1	AB	AFM				0.20	0.30	900	0.46	$120	$480	$12			300	630		
VS2	C	MF	0.22	0.22	5					$2,000	$25	$200	0	0			$28,257	$10,757
VS2	D	MF	0.24	0.24	7					$8,000	$30	$800	0	0				
VS2	ACD	ASSY				0	0	7	0	$15,000	$4,000	$1,500			1&2	7		
VS3	E	MF	0.55	0.31	200					$250	$10	$25	&160&34	138			$75,200	$3,450
VS3	AE	ASSY				0.57	1	170	0.57	$400	$1,000	$40			0	0		
VS4	F	MF	0.58	0.37	25					$500	$150	$50	5&9	16			$4,457.5	$913
VS4	AF	ASSY				0.59	1	12	0.58	$1,000	$450	$100			0	0		
VS4	AF	AFM				0.48	0.82	7	1	$1,000	$4,000	$100			24	2		
VS5	G	MF	0.30	0.30	12					$3,000	$45	$300	0	0			$150,378	$6,378
VS5	AG	ASSY				0	0	10	0	$6,000	$15,000	$600			0	10		
VS5	AG	AFM				0	0	0	0	$6,000	$24,000	$600			0	0		
VS6	H	MF	0.15	0.15	10					$4,000	$80	$400	0	9				$3,400
VS6	AH	ASSY				0.25	1	6		$10,000	$800	$1,000			1	0		
VS6	AH	AFM				0.38	1	5		$10,000	$40,000	$1,000			1	0		
VS7	I	MF	0.18	0.18	8					$3,500	$36	$350	0	7				$13,246
VS7	AI	ASSY				0.05	0.27	6		$25,000	$8,000	$2,500			1	5		
VS8	M	MF	0	0	12					$8,000	$15	$800	0	0				$19,980
VS8	AM	ASSY				0.09	0.09	11		$18,000	$6,000	$1,800			3&0&1	11		
VS9	T	MF	0.70	0.59	25					$2,000	$15	$20	6	10			$1,249	$468.96
VS9	L	MF				0.30	0.43	12	0.50	$300	$25	$30			4&3	7		
VS9	N	MF	0.70	0.53	12					$90	$2	$9	14&0&5	6				
VS9	S	MF	0.95	0.95	10					$160	$8	$16	0	1				
VS9	ALNS	ASSY				0.59	1	5	0.85	$3,500	$500	$350			6&3	0		

Value Stream 1:

Shortage costs of ASSY and AFM (customers) are the first two highest costs; therefore, the model targeted them first and recommended that the delivery performances in those entities be increased to 100% by keeping safety stock for the finished parts. ASSY and AFM can count on receiving their required demand on time for 0.61% and 0.30% respectively; thus, they need to compensate the 0.39% and 0.70 % of *unavailability* of parts by asking manufacturing to keep safety stock.

Then, the third and fourth highest costs are the overage costs of the same entities. Hence, the model suggests keeping some level of safety stock in the raw material (semi-finished part) level as well to lower the level of finished parts' safety stocks. It is shown that procurement can count on on-time delivery performance of supplier(s) for 0.57% and they have to reimburse the remaining 0.43% by having safety stock. As in this case, safety stock has been increased in both levels of supplier and manufacturing, of course before applying the recommendations, the capacity of both should be checked in order to be aligned with the new level of demand and input respectively.

Value Stream 2:

According to the priority of costs, shortage should be removed for the Assembly entity by keeping safety stock for its required finished part. In this case, the manufacturing performance is zero; therefore, having safety stock for the raw materials' level in case improving the input amount to this entity will not make any changes. Consequently, there is no choice but to pay for the holding cost for the finished part, although this holding cost is the second highest cost. On the other hand, as soon as manufacturing performance increases even slightly, the level of safety stock required for the finished part will decrease by recommending holding some safety stock for raw materials.

Value Stream 3:

Again the highest cost is the shortage cost of the finished part and an action required to reduce this cost by making K_p (delivery performance) 100%. As the manufacturing performance is 100% (P_p=1) and based on the formula of $K_p = P_p \times K_i$, the only way to make K_p equal to 1 is by making K_i equal to 1. Therefore, having safety stock for raw material is recommended by the model for this purpose. In sum, in this case, the manufacturing entity has produced whatever they received from procurement; therefore, to improve their delivery performance, the input amount should be improved. Of course, for this kind of change, the capacity of manufacturing should be checked in order to be aligned with its input.

Value Stream 4:

In this case, the highest cost is related to the shortage of finished part required for Aftermarket; hence, safety stock should be kept for this customer. Then, the biggest loss would occur if the company cannot deliver the required demand of ASSY; as manufacturing's performance in response to Assembly's demand is 100% and it can produce whatever it receives from procurement, delivery performance to ASSY will be improved only by increasing input of the raw material to manufacturing. To make a decision about the value of K_i, the model will hit the third highest cost which is the raw material's shortage cost. The selected value for K_i will also affect the level of required safety stock for Aftermarket.

Value Stream 5:

Apparently, it is understood that there is no need for safety stock for Aftermarket as its demand for the next quarter is zero. But, it should be noted that as the manufacturing performance for this customer is zero, safety stock should be considered as soon as demand occurs. On the other hand, for the purpose of cost reduction, delivery performance to Assembly should become 100%. As the manufacturing performance in response to this customer is also zero, the full quantity of the finished part within the replenishment lead time should be kept as safety stock. By improving manufacturing's performance up to 50%, the level of safety stock required to be kept in finished parts will be lowered but still there would not be any recommendation for keeping safety stock for raw material. However, as soon as manufacturing's performance increases by more than 50%, the model will suggest starting keeping safety stock in the raw material stage as well and balancing it to minimize the total cost.

Value Stream 6:

Based on the investigation done for this case, it is known that raw material has quality problems most of the time. With this background, the result of the model does make sense: to keep safety stock in that level of the chain.

Value Stream 7:

The model suggests balancing the level of safety stock by keeping it in both raw material and finished part levels and ensuring the on-time delivery to the customer, Assembly.

Value Stream 8:

This value stream includes one raw material and one finished part with only one customer, Assembly, just as in Value Stream 7. As shown previously, safety stock was kept at both levels; but now the model is suggesting keeping safety stock for the finished part only. The reason is that manufacturing performance is almost zero and improving its input will never help to provide on time delivery to Assembly. On the other hand, the holding cost of the raw material is really greater than its shortage cost; so, it is not beneficial even for lowering the level of the finished part's safety stock.

Value Stream 9:

This sample shows one of the class A finished parts required for Assembly for the selected product family. This finished part has three semi-finished parts (level 2 in finished product's BOM which are L, N, and S in Table 4.1). "L" is an in-house part and is manufactured in ABC. Furthermore, the manufacturing plant requires raw material (T) to produce this part which is procured through the supplier. Part T is in level 3 in the BOM. Therefore, this sample goes far beyond the limitation of levels 1 and 2, and shows that the model is applicable for all stages of the value streams as long as the input data of the model are provided. Manufacturing, receives the two other semi-finished parts (N and S) required for producing the finished part directly through suppliers. Figures 4.1 and 4.2 present the respective value stream and BOM.

It is assumed that there is a bottleneck in the first value stream in Figure 4.1 because the manufacturer does not have the capacity for the requested new level of demand, which includes safety stock. Then the other two value streams can make their delivery performances 100% by keeping safety stock, although the finished product cannot be cleared yet due to the pacer part of the first value stream (if there is no safety stock kept

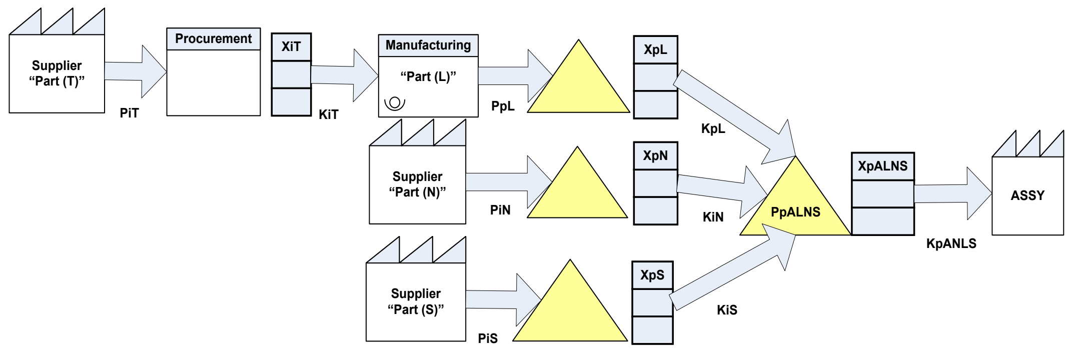


Figure 4.1 Value stream 9

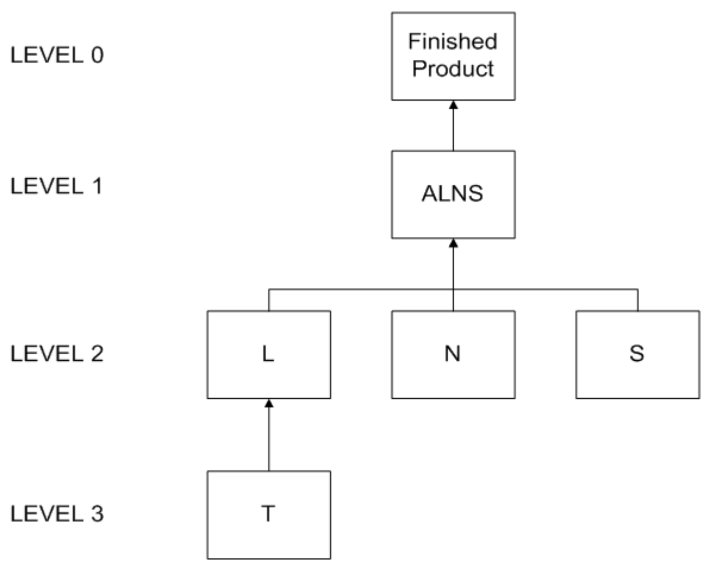


Figure 4.2 BOM

for the finished product). In this situation, there may be some complaints that safety stock must not be kept in the other value streams either since in the end, the company will pay for the holding costs while the finished product cannot be released. The response to this complaint is that if the first value stream comes out of the pacer situation, then another one will become the pacer due to not having safety stock. In essence, the bottleneck always moves. Therefore, for this case, it makes sense to keep safety stock only for two of the value streams although the delivery performance of the finished part will not be 100% due to the low performance of the value stream with the bottleneck. On the other hand, by improving the delivery performances even only for two value streams out of three, holding cost of the finished part based on its formula ($C_{op}\times K_p$-($P_p\times K_1\times K_2\times K_3$)) will be decreased.

This last value stream (value stream 9), can be a representative case to illustrate the error and especially in this case, the overestimating of safety stock result in the analysis of parts in isolation and not within the chain. If the finished part called ALNS (level 1 of Figure 4.2) is being considered separately and a part of its chain, the system may allocate some level of safety stock for that due to the K'_p which is 85%. But, when this part is analyzed within its chain, it is understood that the reason for no availability of the finished part is not due to the last stage performance but to the low delivery performances of the semi-finished parts. Therefore, keeping safety stock in the last stage only increases the holding cost of the system.

4.2 Validation

In this section, historical data on a raw material part will be used for analysis and then compared to the results of the safety stock optimization model in order to validate it.

As illustrated in Figure 4.3, there were periods in the last 5 months during which the company was in shortage and had negative stock and during that period there was no safety stock assigned to this part. On the other hand, the stock situation became better starting in week 13 by allocating 600 units of safety stock. Thus the theoretical safety stock was 0 and 600 for this part during the last five months. The same analysis for part availability percentage through supplier for procurement (P_i) and also the delivery performance of procurement including their safety stock to manufacturing (K'_i) are also done for the same period, as shown in Figures 4.4 and 4.5.

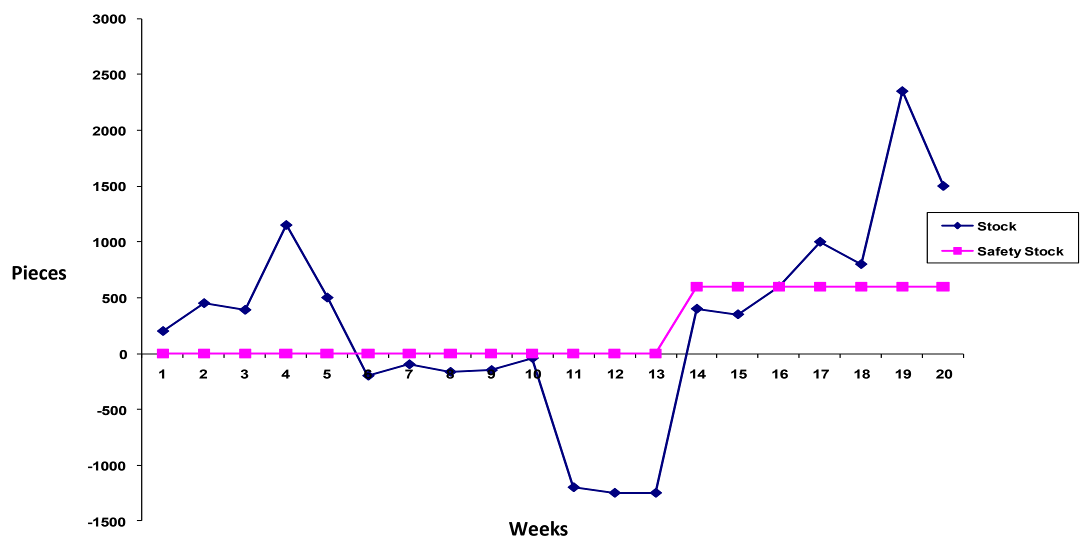


Figure 4.3 Past stock situation and safety stock level

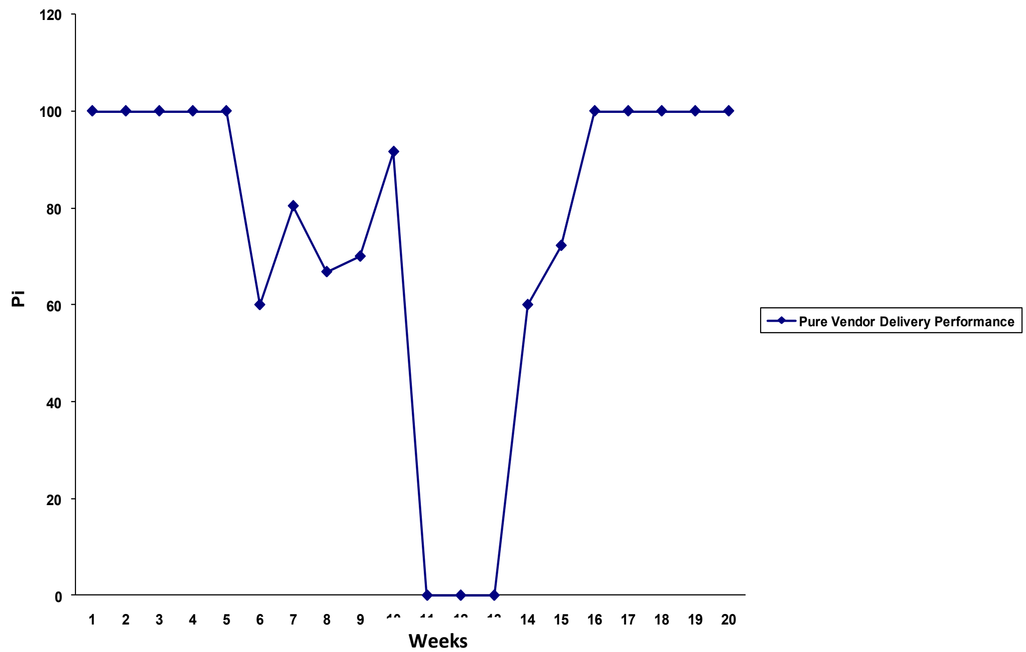


Figure 4.4 Absolute part availability percentage without safety stock

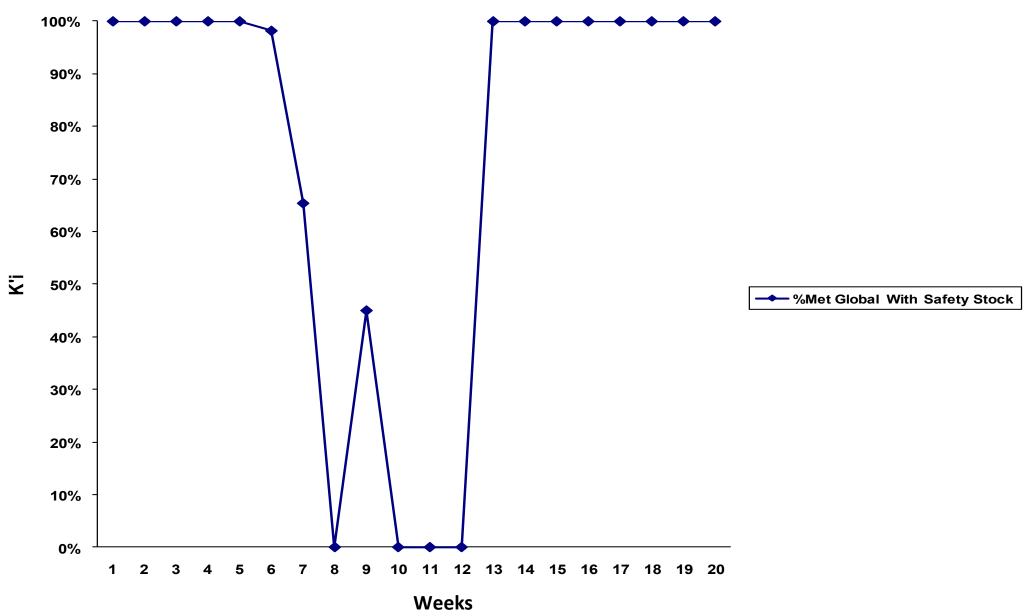


Figure 4.5 Procurement delivery performance with safety stock

It can be seen that the weakness of part availability in weeks 13, 14, and 15 had been compensated by safety stock; therefore, it is concluded that by the historical part availability percentage for this part shown in Figure 4.4, safety stock is essential to guarantee on-time delivery to manufacturing.

The optimization model was then run for the raw material's value stream. The result of the model was 394 pieces for the raw material's safety stock; but of course this level is based on the next quarter ratio of demand. Indeed, the lower level of safety stock recommended through the model is related to the maximum quantity of this part that will be required in the next three months based on the forecast. And this maximum number is being considered in the model to decide the level of safety stock to guarantee the worst case. On the other hand, it is shown through Figure 4.3 that by keeping 600 pieces of safety stock, the level of stock is going to be increased and this is not a desired case as holding cost is associated with this increase; therefore, lowering the level of safety stock does make sense.

Figures 4.6 and 4.7 show the historical data of three factors, FFR (%), safety stock fulfill rate (SS FR%), and number of parts with quality issues (QN in pieces) for two different parts. What these charts communicate are provided as well and they are aligned with the safety stock model's results obtained for the respective parts. As can be seen in Figure 4.6, there was no quality issue for the part from January to December; however, safety stock is required to compensate for the low delivery performance of the system. The FFR of the system for the part analyzed through Figure 4.7 can be improved by 50% by solving the quality issues. In addition, safety stock is essential for increasing the FFR to 100%.

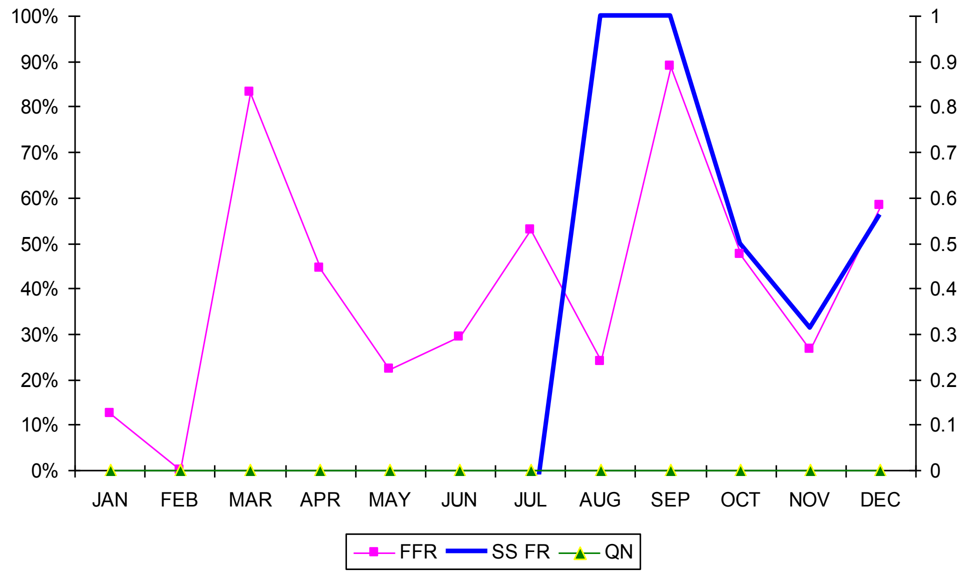


Figure 4.6 FFR,SS FR, QN

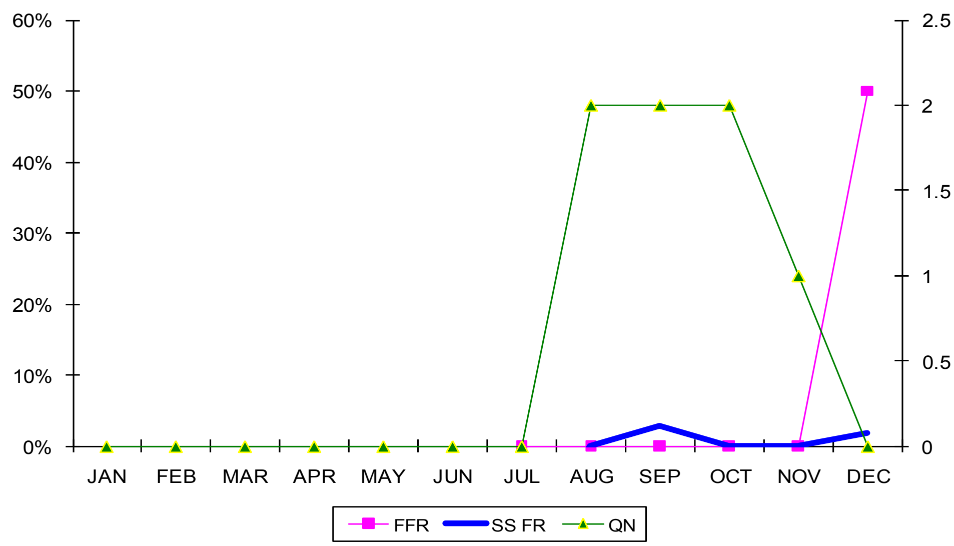


Figure 4.7 FFR,SS FR,QN

This section proved the necessity of safety stock for compensating unavailability of parts due to uncertainties in the supply chain such as bad delivery performances or quality issues. In this section the results of the optimization safety stock model were validated with a real case in the company under study.

4.3 Discussion and implications

Re-sourcing of the suppliers is a potential solution for those with low delivery performances and quality problems. Increasing the capacity of manufacturing and improving its quality would be a solution for low availability percentage at semi-finished and finished parts level.

In the cases that the company requires keeping some level of safety stock due to the bad performance of vendors (low delivery performance, low quality), it is recommended that a VMI system be applied to have safety stock at the vendors' place.

The existing FFR report in the case company for the Aftermarket entity is based on their forecast demand instead of their firm orders; therefore, the model is not capturing accurate delivery performance record for these. By deciding on the level of safety stock based on the forecast demand, we would put safety stock on top of the safety stock because forecast demand is itself a kind of buffer stock. To solve this problem, it is recommended that ABC design an FFR report specifically for Aftermarket in order to capture the performances in response to only firm orders.

There may be some parts that are dual sourced and there is a quota arrangement between different suppliers, but the FFR report being used in the case company does not include the vendor field in its results. Therefore, it is recommended that the supplier field in the FFR report be considered as well to allow the company to recognize their delivery performances separately and consequently be able to make decisions about re-sourcing more accurately.

One of the other factors other than delivery performance or service level of the suppliers in making decisions in the dual source cases is the *waiting time* for receiving the late parts. Indeed, the company as a customer will select the supplier with the lower waiting time among the ones with the same service level. One way of tracking the waiting time of the supplier is through the calculation of the period within the replenishment lead time in which the company had negative stocks; but it is subject to keeping stock of each supplier separately to be able to relate its negative period to the corresponding supplier. Now consider a case that the supplier of a specific required raw material has the delivery performance of 50%, demand is one piece per week, its replenishment lead time is 10 weeks, and its waiting time is 2 weeks. Assume that the worst case for its q_i for the next quarter is 10 pieces. And again assume that it is the case that the model suggests keeping safety stock for the remaining 50% of the time that the supplier is late, which is equal to 5 pieces. This level of safety stock is equivalent to 5 weeks of demand, although the company will receive its late demand after 2 weeks according to the waiting time of the supplier. Therefore, the company does really need safety stock of 2 weeks instead of 5 weeks. Hence, no matter if it is a dual source case or not, it can be concluded that waiting time is also an important factor for determining the optimum safety stock.

If there is safety stock for the finished assembled product or it is scheduled for build ahead, sizing the required safety stock within the chain should be done by taking account of these factors as well. One way to get them involved is by converting them to the weeks of demand for each stage and comparing them with the suggested amount of safety stock (as the method suggested for waiting time). But the time lag between the time that we put safety stock for the finished product or build ahead and the time that it is received should also be considered; otherwise, reducing the safety stock within this period by counting on these factors will put the system in a shortage situation.

For some cases where unavailability of a part is solely related to low delivery performances and not to quality issues, safety lead time can be applied instead of safety stock.

Delivery performances of some parts in their last stage are very low due to different engineering issues such as changing the layout and design continuously. Therefore, recommendation of the model to have safety stock for these parts will make sense only if the cost of rectifying of these parts is less than their shortage cost.

If the model suggests increasing the level of safety stock for a specific stage, the company will receive it by the end of the *total lead time* of the chain related to that part. Therefore, if the company adds the extra pieces of safety stock to its demand, it will allow all purchase orders to be expedited, although this extra amount is not the actual demand and it is required for safety stock. Hence, the company must inform the suppliers that it needs this portion of demand for their next lead time. On the other hand, it is really important to take into account the lead time of the whole chain, otherwise, it will put the company in a shortage situation. As a result, knowing the existence of this time lag by adding the required safety stock to the company's demand until receiving it through the chain, the period for calculating q_i and q_p can be selected more accurately. It should be noted that after selecting this appropriate period, standard cost of the parts should also be updated accordingly.

The quantity ordered used in the calculations for those parts that are strategic ones should be validated with the responsible value stream managers. Indeed, quantities of this kind of parts could be really greater than the number results in through the mentioned way of calculation for them in Section 3.5. There are different indicators that make a part strategic such as the critical parts that are single sourced, or the parts that have limited suppliers or the parts with the resourcing strategy. For example, there could be a single sourced critical part which is received in a batch and based on the experience it is known that if one part of this batch has a quality issue, there is a high possibility that the entire batch needs to be scrapped. Therefore, by having the correct level of safety stock for this part, the company can survive and save the supplier's lead time. The safety stock optimization and simulation models developed in this research are applicable to any kind of manufacturing system that is moving towards applying lean principles. The safety stock models presented in this research can be applied to create flow in their supply chain as well as to simultaneously reduce logistics costs. The optimization safety stock model in this study can be adjusted according to the requirements of different value streams of any supply chain. The safety stock simulation model in this research also addresses key metrics for supply chain performance measurement from which any system can leverage.

The simulation inventory model developed in this research can be extended to be applicable to any system that attempts to increase its inventory turnover. The assumptions and hypothesis of the model will be changed according to the specifications of the business. The model's tool and its inputs will be adjusted and modified as well.

In summary, the guidelines and implications provided in this section are useful for any manufacturing system.

Chapter Five

Conclusions and Future Research

In this chapter we present conclusions of the research carried out in this thesis. Future research directions regarding to the safety stock optimization model are also discussed.

5.1 Conclusion

This research extends the work of Aleotti Maia and Qassim (1998). They proposed a nonlinear safety stock optimization model for a system with n suppliers, one manufacturer and one customer with the objective of total inventory cost minimization. In this study we extended the model to be applicable to the whole supply chain of a generally structured multi-stage manufacturing system. Proper required index, parameters, and variables have been introduced and added more flexibility to the model implementation. In addition, the possibility of stockout for all materials at any stage of supply chain (raw material, semi-finished part or finished part) has been taken into account in the model of this study; although it was assumed previously that the material (raw material or semi-finished part) required by manufacturing is always available. This consideration makes the model more realistic. In this research, the safety stock optimization model is provided with the objective function of total logistic costs minimization to result in not only the optimal level of safety stock but also the optimal location of it across the supply chain. The constraints of the model provided for the boundaries of the delivery performances of each stage of the supply chain. Then, we applied the optimization model in a practical real-world problem with different possible value streams. We accurately defined the inputs of the model such as shortage and overage costs and also quantities of the parts. Lingo 11.0 was used to solve the non-linear optimization model.

An analysis of the results shows that the weakness of the supply chain must be compensated with safety stock, while it is optimized to meet the desired objective of the business. It has been shown in the thesis that in optimizing the safety stock based on a cost minimization objective, not only its level but also its location in the supply chain is important. In fact, by keeping safety stock in upstream stages, there will be savings in holding costs. On the other hand, by keeping safety stock in downstream stages, there will be savings in lead time. Therefore, these two options must be traded off towards optimizing safety stock location for minimizing the total logistics costs. Through this procedure, any business can improve its profitability and also become a superior competitor with its chain.

Providing supply chain performance measurement metrics that can be integrated is a challenging task. In this study we have introduced some of these metrics such as First Fill Rate, On Time Delivery, safety stock coverage, among others. We also linked them together and developed a safety stock simulation model based on them that supports the results of the optimal level and location of safety stock. This safety stock model consists of some matrixes that allow us to assess the performance of any stages of the supply chain in a matter of safety stock level and location.

It also has been shown in this study that having efficient inventory is dependent on having efficient safety stock. Therefore, with the optimum level of safety stock as an input, an efficient inventory model was also developed to achieve the goal of being lean and improve inventory turns. Access 2003 with SQL coding was used as the tool for the inventory model. On the other hand, as the assumptions of the inventory model provided in this research come directly through the case company's system, it is necessary to validate the model. This was done through benchmarking to enhance the process robustness. With the output of the EI model, each entity can define a guideline to move towards the objective of becoming lean and also improve turns.

The first contribution of this research is developing a nonlinear optimization safety stock model applicable for the whole supply chain. Thus, the applications are not limited to specific stages or levels of the chain. The second contribution of this study is applying the proposed safety stock optimization model to a real world case company. Through this contribution, it has been shown that analysis of any part in isolation and not within the chain will result in errors (overestimating or underestimating) in safety stock calculation. It also proved that in optimizing the safety stock, not only its level but also its location within the supply chain is really critical. The third contribution is developing a safety stock simulation model based on the supply chain performance metrics which sustains the results of the optimization model. It involves providing the most appropriate metrics and making linkage among them to assess the supply chain performance while making decision about level and location of safety stock. The last contribution of this research is developing a simulation inventory model with the objective of increasing the inventory turns. Although this model has developed based on the hypothesis and assumptions of the case study, it can be extended to be applicable in any other business.

5.2 Future research for safety stock optimization model

There are a number of ways that the research done in this thesis can be improved. If a part is procured through more than one supplier, the current model tracks their performance with only one average number representative of them all. In future work, the model may be extended by increasing the accessibility of the other required input data to decide on the level of safety stock for each of these suppliers separately.

Due to the inaccessibility of the required data, the model is currently limited to the last two stages before the customer in the chain. Again, by enhancing the visibility and control of the upstream stages in the chain, the model can be applied for each specific part from its starting point until the end of the chain. Furthermore, by increasing the accessibility of the data, the cost of shortage of raw material/semi-finished part can be more accurate by adding the re-sequencing cost of manufacturing.

The cost of shortage of the finished part required by Assembly can be more precise by making the average days of shortage weighted based on the frequency of its occurrence (increasing or decreasing trend of shortage).

Another avenue for future work for this research would be taking into account the factors of waiting time for receiving the late parts, safety stock for the finished assembled product, and build ahead in making the decision for the safety stock.

In order to have a high level view of safety stock kept across the chain, this model can be applied to the aggregate level of stages and entities involved in the chain instead of applying it to the part level. Indeed, q_i and q_p will be the total demand of the downstream stage in a specific period seen by its upstream stage (kits of parts instead of one part) and delivery performances will be delivery performance of each stage to its downstream stage in respond to its whole demand. The parts that were historically pacers with the maximum number of shortages within the total demand of each stage will be selected as the representatives for calculating the shortage and overage costs of the stages for determining the location of safety stock.

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Appendix A

Assume a case that there are two different finished parts manufactured in the same plant and they require a common raw material. Model formulation and value stream for this case would be as (8) and Figure App.1:

$$
\begin{aligned}
&MinC = C_{si}q_i(1-P_i)+C_{oi}q_i(K_i-P_i)\\
&+\sum_{p=1}^{2} C_{spu}q_{pu}(1-K_{pu})\\
&+\sum_{p=1}^{2} C_{opu}q_{pu}(K_{pu}-(P_{pu}\times K_i))
\end{aligned}
$$

$$
\begin{aligned}
&SubjectTo:\\
&K_i \le 1 && i=1\\
&K_i \ge P_i && i=1\\
&K_{pu} \le 1, && u=1, p=1,2\\
&K_{pu} \ge P_{pu}\times K_i, && i,u=1, p=1,2
\end{aligned}
\qquad (8)
$$

Procurement sees the summation of demands for both finished parts through manufacturing at once and not separately. Therefore, mathematical proof of (9) is provided to make sure that the used formulation is accurate. Indeed, it is shown that manufacturing plant absorbs the input ration of the raw material based on its performance for each finished part:

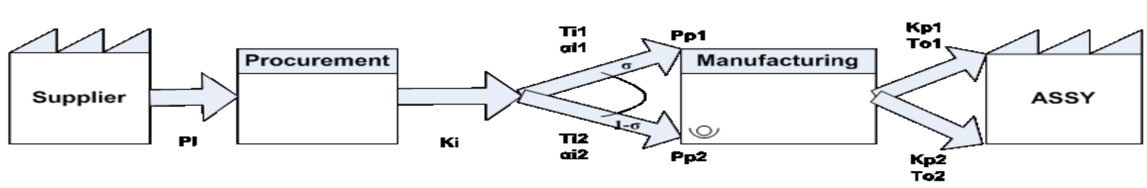

Figure App.1 Value stream

$T_i = Total\ Input$
$\alpha_i = Input\ On\ Time$

$T_{o_1} = Total\ Output\ 1$
$\alpha_{o_1} = Output\ On\ Time$

$T_{o_2} = Total\ Output\ 2$
$\alpha_{o_2} = Output\ On\ Time$

$$K_i = \frac{\alpha_i}{T_i}, \quad K_{p_1} = \frac{\alpha_{o_1}}{T_{o_1}}, \quad K_{p_2} = \frac{\alpha_{o_2}}{T_{o_2}}$$

$T_{o_1} + T_{o_2} = T_i$ $\quad$ $(Input = Output)$
$\alpha_{o_1} \geq \alpha_{i_1} \times P_{p_1}$ $\quad$ $Because\ of\ Safety\ Stock$
$\alpha_{o_2} \geq \alpha_{i_2} \times P_{p_2}$ $\quad$ $Because\ of\ Safety\ Stock$

$\alpha_{i_1} = \sigma \times \alpha_i$
$\alpha_{i_2} = (1-\sigma) \times \alpha_i$

$T_{i_1} = \sigma \times T_i = T_{o_1}$
$T_{i_2} = (1-\sigma) \times T_i = T_{o_2}$

$$K_{p_1} = \frac{\alpha_{o_1}}{T_{o_1}} = \frac{\alpha_{o_1}}{\sigma \times T_i} \geq \frac{\alpha_{i_1}}{\sigma} \times \frac{P_{p_1}}{T_i}$$
$$= \frac{\sigma}{\sigma} \times \frac{\alpha_i}{T_i} \times P_{p_1} = P_{p_1} \times K_i$$

$$K_{p_1} \geq P_{p_1} \times K_i$$

$$K_{p_2} = \frac{\alpha_{o_2}}{T_{o_2}} = \frac{\alpha_{o_2}}{(1-\sigma) \times T_i} \geq \frac{\alpha_{i_2}}{(1-\sigma)} \times \frac{P_{p_2}}{T_i}$$
$$= \frac{(1-\sigma)}{(1-\sigma)} \times \frac{\alpha_i}{T_i} \times P_{p_2} = P_{p_2} \times K_i$$

$$K_{p_2} \geq P_{p_2} \times K_i \qquad (9)$$