# DESIGN AND ANALYSIS OF A MATERIALS MANAGEMENT SYSTEM FOR BOEING COMMERCIAL AIRPLANES' (THE BOEING COMPANY) METALLIC RAW MATERIAL SUPPLY CHAIN

WITH A FOCUS ON LEAD TIME MANIPULATION AND CORRESPONDING EFFECTS ON INVENTORY AND COST

by

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## Abstract

The purpose of this project is to identify the costs associated with an aggregation strategy run by Boeing Commercial Airplanes. In order to identify these costs, a rudimentary replenishment system must be designed for the supply chain due to the fact that there is currently no such system in place. This replenishment system will be used to create a model (created in Excel) to calculate the total annual costs of the system. The model must allow changes to some of the important inputs such as mill performance measures and lead times and report the resulting changes in the total annual cost. Boeing has contracted out the responsibilities of operating the aggregation strategy to an outside company called TMX Aerospace. TMX operates the system out of warehouses that also act as distribution centers (metal moves from the metal mills to the TMX warehouses and then to the suppliers). Among the many benefits that demand aggregation provides, TMX also provides a service known as lead time manipulation. This service essentially transforms a long lead time from the mills to TMX into a dramatically shorter lead time between TMX and the suppliers. The costs of this service are particularly important for this project. The results of this study will be used to identify an optimal replenishment strategy and the costs of running the operation. In addition, this project will pave the path for a supply chain management software package to be implemented at the distribution center in the future.

## Introduction

As a manufacturer of commercial aircraft, Boeing Commercial Airplanes (BCA) orchestrates a complex supply chain. The following project is meant to initiate the creation of a general tool that should eventually be capable of analyzing all components that Boeing makes or buys. Due to the interests of the stakeholders, the priority of this project is on the metallic raw material and as discussed later, this will be scoped down even further.

Boeing utilizes an aggregation strategy that pools together the metal demand from all of BCA's internal manufacturing functions along with the demand from the company's suppliers. Boeing takes on the responsibility of purchasing the metal and distributing the metal to its suppliers. In the process, Boeing offers lead times to their suppliers that are much shorter than the lead times between the mills and Boeing-designated storage and distribution locations. This requires precise forecasting and coordination on Boeing's part. The project described below involves a model and a sensitivity analysis that are intended to expose the effects of lead time variations throughout the company's complex supply chain. However, before this analysis can be performed, the model must be developed to best represent the current situation.

Boeing absorbs increased costs in order to reduce risks and provide reduced customer lead times. The main objective of this project is to determine how much the costs are increased in order to provide these benefits and whether these increased costs are worthwhile. In addition, the sensitivity analysis will reveal how factors such as bad customer forecasts impact the stability of the system.

Along the way, modifications will be proposed to the current system and a new materials management system will be designed to best support the operation of managing the metallic raw material supply chain.

**Problem Statement**

There is currently no way to identify the costs of operating the described aggregation system (through TMX) and the use of lead time manipulation. The reason for this is that the system described is actually not currently in operation.

**Project Scope**

- Conduct literature review to determine if previous research has been conducted on the same or similar topics. Utilize findings in such literature as a baseline for performing current research study. This previous research will be used as an aid but the results from this current study will also be contrasted to those of the literature.
- Create a model that would simulate lead time variations within BCA's supply chain (including both internal and external components which mean both internal and external suppliers are involved).
    - First step is to document and model the current state
        - Data to be provided by The Boeing Company
        - Utilize one example product to start and create a steady state model of the product

        - Experiment with different variations within the system and observe the change in cost, risk, and performance (possible lead time to promise the customer, the lower the better)
        - Use these results to develop a model that would effectively represent subsequent scenarios
    - Priority is to focus on metallic raw material supply chain
- Present and examine “what-if scenarios”
    - Unlike in the previous task, these what-if scenarios are presented for individual situations and observed in order to collect data and not for the experimental purpose of developing a model
    - Consider economic implications of each model (inventory costs, shortages)
    - Perform sensitivity analysis to determine which factors are most influential
    - Perform in-depth analysis on factors that are most likely to derail the current state
        - Customer LT
        - Customer forecasting effects
        - Random LT variations that results in a disruption in the relationships between the Mill and BCA and BCA and the supplier
        - *Fixed Mill LT - * to indicate that Mill LT will not be one of the factors to be examined. Mill LT’s are assumed to be fixed.

**Project Deliverables**

1) Model an interface that would allow users to input lead time variations and be presented an output showing the changes to the current plan. This output will include the severity of these discrepancies and reveal possible methods of dealing with the situation.
2) Analysis of presented “what-if scenarios.”
3) Complete technical report including literature review.
4) Business presentation of problem, analysis, and findings.

**Technical Approach**

1) Model current state – create fabricated representation of the system that would produce the best results
2) Introduce changes to the current state
3) Analyze effects of changes
4) Determine methods to resolve issues in the supply chain and improve it
5) Verify proposed improvements

At the moment, it seems that this analysis is best done in Excel. Additional statistical analysis is conducted in either MiniTab or JMP. ProModel will be evaluated as a possible tool for modeling the situation. Data will be supplied by BCA Supplier Management and be processed utilizing concepts from inventory management learned in classes such as the Operations Research series, IME 410, and IME 239. The most prominent of the topics covered in such classes involve materials

management principles such as EOQ, MRP, inventory costs (including storage and obsolescence), and manufacturing systems (Build-to-Stock, Build-to-Order, etc).

## Background

The initial phases of this ongoing project will deal with Boeing Commercial Airplanes' metallic supply chain. At the very beginning, the project will be even more specific and narrow the scope down to only aluminum. Aluminum has been and continues to be Boeing's most utilized metal within its aircraft production (including the metal used by their suppliers).

In order to account for the amount of metallic raw material that Boeing uses, one must move further upstream in the supply chain. Those who have taken a tour of the Boeing facility in Everett, WA will have only witnessed the final assembly stages of the aircraft production process. The Boeing plant in Everett is the largest building in the world by volume (www.boeing.com: recognized by Guinness Book of World Records) for a reason. This expansive manufacturing facility is the culmination of extensive planning and execution by tens and tens of thousands of employees (From Boeing's website: www.boeing.com, the combined amount of employees working for any of The Boeing Company's two major business units and three supporting units is over 170,000). Parts and services are routed from all over the world to this facility where the finishing touches are put on the airplanes so that they can be delivered to the customer. As such, very little raw metal is consumed in this facility.

A majority of the metal is fed to internal and external suppliers. In turn, these suppliers are responsible for feeding the Everett plant with the necessary parts and assemblies. Internal suppliers are defined as manufacturing organizations that are owned by The Boeing Company. These suppliers are allocated a different company

number for accounting and logistics purposes. For example, a Boeing manufacturing plant that is responsible for manufacturing the empennage of an airplane from raw aluminum is assigned an LC (Logistics Company) number and considered an internal supplier. External suppliers are defined as companies that are independent of Boeing ownership but who have signed contracts with The Boeing Company to produce parts for the company at an agreed-upon price.

As mentioned before, Boeing not only manages the supply chain of metallic raw material for its internal suppliers and machine shops but also for many of its external suppliers. Boeing has offered this service to their external suppliers for many years.

The supply chain relationship that Boeing orchestrates begins at the mills from where the raw material is purchased. (Note: Although the metals that Boeing and its suppliers acquire from the mills are not the very most raw material in the grand scheme, it is considered the raw material for this relationship.) This relationship is represented in the process map below (**Figure B-1**).

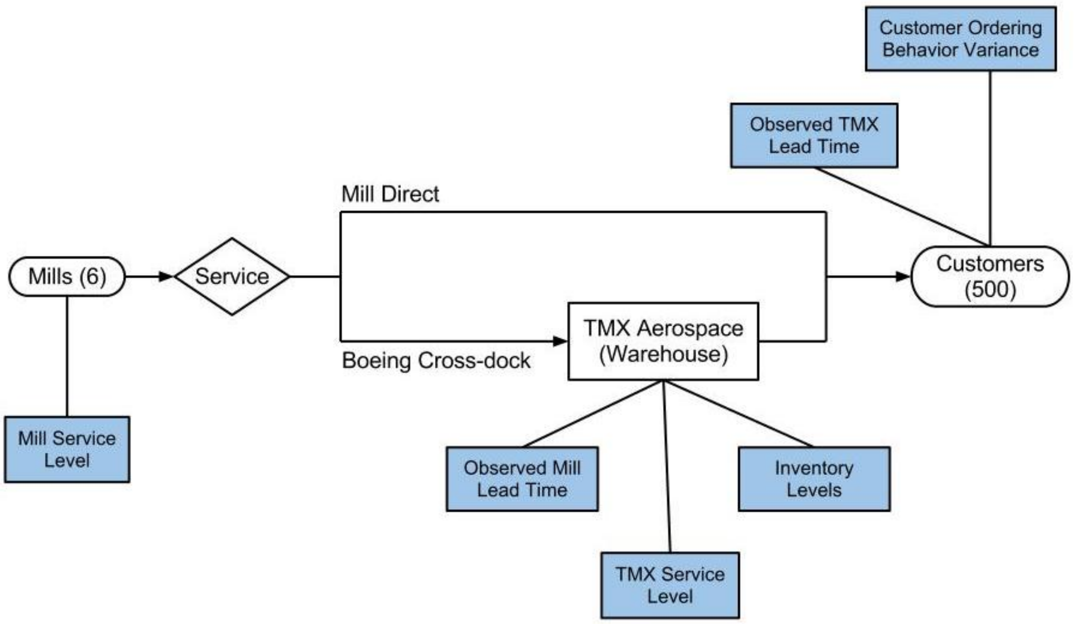


**Figure B-1.** Process map

Once the metal is ready for delivery at the mill, the metal will be routed through one of two predetermined services. The first service is known as "mill direct." Mill direct is the service in which the metal is delivered directly from the mill to the customer. The second service is known as "cross-docking." Boeing has delegated many responsibilities associated with cross-docking to the company TMX Aerospace (a ThyssenKrupp Materials Services company). The "Company Overview" on the TMX Aerospace website (www.tmxaerospace.com) describes the services that it provides to Boeing Commercial Airplanes:

*"The focus of TMX Aerospace is to optimize material and information flow for the Boeing Commercial airplane supply chain. This includes the coordination of order management, purchasing, storage, processing,*

*packaging and delivery functions for the world-wide Aerospace community. With its headquarters in Kent, Washington, TMX Aerospace currently inventories, processes and ships material from four locations in Auburn, Washington; Wichita, Kansas; Wallingford, Connecticut and Santa Fe Springs, California. Sales, Purchasing and Administrative functions are handled out of the divisional headquarters."*

An important bit of information acquired from this description is that TMX Aerospace targets only the commercial sector of The Boeing Company, and as such, this project will only be concerned with Boeing Commercial Airplanes. TMX Aerospace does exactly what the description states. Its main function is to aid BCA in the materials management aspect of the metallic raw material supply chain.

A big obstacle for this project is due to the fact that Boeing and TMX do not currently have a well-structured system for managing the inventory of metallic raw material. There isn't a precise forecasting system to predict future customer orders and the reason for this is that there isn't a pressing need for this kind of system. For years, Boeing has been sitting on a huge pile of inventory. This inventory has accumulated due to years in which the output of the company shrunk dramatically as a result of the recent recessions. For reasons that are not within the scope of the project, the company continued to purchase large amounts of metal from the mills despite the decline in demand. For the recent years, the company has been pulling product from this pile of inventory and also from new orders. Once this pile of inventory has depleted, Boeing is

looking towards maintaining a close to JIT system. This is the system that this project will revolve around.

As mentioned earlier, this project is focused upon the effects of lead time on the overall system cost. However, there are other factors that must be included in the equation. These factors are the service levels (at the mills and at TMX) and inventory levels. The service levels measure the delivery performance of the entity. For example, the service level at the mills measures the percentage of times that the mills deliver the right product at the right time. Inventory levels are exactly as they sound: the amount of inventory held at a location at a moment in time. The service levels affect the inventory levels because they determine the amount of safety stock that must be held. This will be covered later. In return, the inventory levels are a huge contributor to the increased amount of funding that BCA must provide to keep this operation running.

BCA's relationship with TMX Aerospace has grown increasingly more complicated. TMX has begun to offer additional value-added services (such as cut-to-size) to Boeing suppliers. These variables would introduce additional cost factors into the equation. These variables are not within the scope of this project. Once again, this project is concerned with the transportation and storage of materials that occurs between the mills and Boeing suppliers and the associated lead times, inventory levels, service levels, and costs.

So now a huge glaring question is why would BCA absorb these increased costs to perform this cross-docking operation? Although quantifying the benefits of cross-docking (or more specifically the lead time manipulation aspect of the operation) is not

within the scope of this project, it is beneficial to question and think about the underlying motivations. This aggregation strategy was put in place in order to take advantage of the benefits that come with pooled demand. These benefits are:

1. Increased demand leads to increased leverage at the mills
2. The possibility of greater quantity discounts
3. Boeing has more visibility and control over its supply chain.
    a. Boeing absorbs the risks
    b. With the reduction (almost removal) of the risks associated with flow of material from its own suppliers, the Boeing suppliers should achieve more stable supply chains.

Point 3. above is the one most closely associated with lead time manipulation.

The Boeing suppliers obviously receive their own benefits by utilizing this service through TMX Aerospace:

1. Significantly reduced lead times
2. Reduced risk
3. Stable prices: This last point is a hugely discussed issue within BCA but will not be addressed in this project because it is not within the declared scope.

All of these benefits to Boeing itself and to its suppliers will come at an increased cost to Boeing. The analysis of these costs is a very important part of this project. One of the more difficult tasks surrounding this analysis is determining whether these increased costs are worthwhile. In order to determine this, a cost savings must be assigned to the

increased visibility and control over Boeing's supply chain. This visibility and control would help to reduce risks within Boeing's assembly processes. If Boeing can reduce the variation in lead time from the suppliers, planning and execution would be a whole lot smoother. Forecasting would be much more accurate and a lot less firefighting would be required. All of these benefits are theoretically sound but very difficult to quantify and put a monetary number to.

Ultimately, the stakeholders of this project are hoping that continued research in this area will reveal that this operation is indeed beneficial to Boeing and its suppliers as believed and is a worthwhile operation. Another purpose is to show the suppliers that they are gaining immensely from this arrangement and that Boeing is paying for it. This will offer Boeing more leverage when discussing future contracts with the involved suppliers.

## Literature Review

Boeing recognizes the TMX function as "cross-docking," but familiarity with what TMX actually does has raised some issues. A quick literature review focused on the concept of cross-docking, its development, and its associated benefits will confirm that the function that TMX performs does not match the fundamental description of cross-docking. Cross-docking was created in order to reduce the lead time of materials by improving the flow. Simultaneously, cross-docking seeks to eliminate processes (mainly storage and order picking operations) during the transportation of these materials. The basic idea is to route the materials from the receiving area straight to the shipping area as soon as possible and with as little in between as possible (Yan and Tang, 2009). In theory, material would flow from the incoming truck directly into the outgoing truck (Bartholdi and Gue, 2004). The main goals of cross-docking are to reduce costs and lead times by eliminating unnecessary operations. In more detail, cutting these unnecessary operations would reduce personnel costs and the cost of holding inventory. Lead times would be reduced and accelerated by replacing time intensive operations with operations that require more coordination but significantly reduce the resulting processing times. A simple equation balancing all of the added material handling costs with the cost savings will make one simple fact clear. Cross-docking is beneficial if the cost savings in transportation and inventory outweigh the increased material handling costs (Bartholdi and Gue, 2004). The bottom line is that, in theory, no parts are actually stored at the cross-dock (Yan and Tang, 2009). Yan and Tang refer readers to the following papers for additional information about cross-docking: Clyde (1992), Cook et

al. (2005), Ackerman (1997), Harrington (1993), Gue (2001), Schwind (1995), and Cooke (1997). On the other hand, the TMX cross-dock operation is utilized in a different manner. TMX and Boeing collectively own a healthy amount of warehouses. These warehouses act as a combination of a distribution center and "supermarket" for the suppliers. In this way, these warehouses are able to hold inventory and safety stock in order to provide the Boeing suppliers with materials at a much shorter lead time than the mills themselves are able to provide. It also acts as a mechanism for pooling together demand and therefore also pooling risk. From the article by Yan and Tang, "a traditional distribution center (DC) holds goods first, and then picks-up and delivers goods to meet stores' demands later." From this definition, it is clear that TMX Aerospace serves Boeing in a way that is more like a traditional distribution center than a cross-dock. In addition to reviews about dynamic lead times, supply chain management, and materials management, research about managing inventory and lead times at distribution centers were also explored.

Initial research into the field involving lead time, inventory, and pooling has shown that this TMX cross-dock operation resembles the relationship between suppliers, distribution centers, and retailers. This relationship deals with the retail industry and the goals of the TMX operation are very similar to those that are widespread across the retail world. As a clarifying statement, an analogy is being drawn between the TMX cross-dock operation and retail distribution. The mill in the TMX operation is likened to the supplier in the retail model, the warehouses (TMX and Boeing) with the distributions centers, and the Boeing suppliers with the retailers.

In addition to performing as a distribution center, TMX Aerospace must also provide the aforementioned “supermarket” ability to the supply chain. Because of this, portraying TMX and Boeing as the retailer (“supermarket”) would also be accurate. In the end, TMX and Boeing can be seen as a mix between a distribution center and a retailer. In addition to the receiving, storage, order picking, and shipping operations that a DC needs to provide, TMX Aerospace must hold inventory far exceeding the amount of the traditional safety stock to drastically reduce lead times. In order to reduce a 40 week lead time from the mills to a 4 week lead time to the Boeing suppliers (these times are approximate but are a good example of the real life discrepancy in lead times), TMX Aerospace must forecast the demand from the Boeing suppliers and hold enough inventories (plus a newly adjusted safety stock proportional to the new increased amount of inventory) to satisfy the demand when it appears. An analogy can be drawn to a retail store. Consider the example of a bottle of water at Target. Assume a lead time of 1 week for the lot of bottles of water to be received at Target from the water distribution company. When a consumer enters Target, they expect the product to be ready for them to purchase. This translates to essentially a lead time of 0. This is why Target must maintain a forecasted amount of bottles of water at each store. This is the inventory that Target must hold in order to reduce the 1 week lead time from the water distribution company to the 0 week lead time that it must offer to consumers in order to be competitive.

It is extremely difficult to locate literature that discusses the exact topic at hand. Searches for lead time reduction and lead time manipulation tend to lead to lean

manufacturing disciplines that seek to reduce lead times by improving the flow of material through a system and by making the system itself more efficient. These strategies aim to reduce the amount of time and resources spent in the 5 elements of a manufacturing cycle and the operations that support it.

**Operations**

1) Receiving
2) Storage
3) Manufacturing
4) Shipping

**5 Elements of a Manufacturing Cycle:**

1) Waiting (Wait Time)
2) Transportation (Move Time)
3) Queuing (Queue Time)
4) Set-Up (Set-Up Time)
5) Processing (Run Time)

The 5 elements of a manufacturing cycle are directly interpreted from the 5 elements that constitute manufacturing lead time (MLT). MLT is defined as "the time normally required to produce an item in a typical lot quantity." (Arnold et al., 2012) MLT and the manufacturing cycle only account for the actual manufacturing processes and do not account for the other operations that support it.

According to Ng and his colleagues, most cycle time reduction research targets only manufacturing lead time (Ng et al., 1997).

The same methods of lead time reduction could be utilized for environments other than manufacturing, such as warehousing/distribution and retail. It is a fundamental goal of lean manufacturing to cut down on costs and reduce lead times. In lean, the two go hand-in-hand and should be pursued simultaneously. Goal is to reduce inventories and lead time. Never increase inventory except for safety stock. In supply chain work, a supply chain's service level is balanced against safety stock levels. Increasing service levels will generally result in increased amounts of safety stock. However, there are methods of improving both at the same time. These strategies are: information centralization, specialization, product substitution, and component commonality. Any of these strategies that can be applied towards the Boeing scenario should be employed to further improve the efficiency of the system. But these are not the proper solution to the problem at hand. It has been difficult finding research that considers the situation where the lead time from the supplier cannot be changed and the distribution center must provide a reduction in lead time to the retailer.

The most relevant article found is that by Park, Lee, and Sung (2009) titled "A three-level supply chain network design model with risk-pooling and lead times." This article discusses the issue of how increasingly uncertain demand from customers has increased the need for a risk-pooling system in today's competitive environment. Risk-pooling is a strategy that aggregates inventory at distribution centers as a method of increasing service levels. Therefore, the article is focused on supply chains that involve suppliers, distribution centers, and retailers. This is exactly the problem that this project is seeking to resolve. However, further reading of this article will reveal that the main

premise is to formulate a programming model that will identify the optimal pairing of the different entities involved and the optimal locations of distribution centers. This complicated heuristic will not be beneficial for this project at all.

Muharremoglu and Tsitsiklis' article "Dynamic Leadtime Management in Supply Chains" briefly touches on a subject that is very close to the topic of this project. The article mentions that "one way to hedge against random fluctuations of demand in supply chains is to keep inventories at various points in the chain." This statement completely embodies the underlying concept of this project. The article also points to a topic known as multi-echelon inventory management. However, the article continues to state that its focus is on another method of responding to demand fluctuations in supply chains. This method is to introduce flexibility into the supply chain (and therefore make the lead times within the supply chain flexible as well) so that there are many options for actually changing the individual lead times within the supply chain. Essentially, these are firefighting operations such as expediting processes and working around the problem at hand.

After a quick search, it was apparent that the field of multi-echelon inventory management is very broad and encompasses the entire field of study relating to supply chains with multiple locations between the customer-facing distribution outlets and the suppliers.

It is not possible to claim that this literature review was exhaustive but through a more than reasonable amount of effort, no results were found that completely discussed the topic at hand.

Through TMX Aerospace, Boeing Commercial Airplanes is utilizing a very unconventional method of practicing lead time reduction. Most (if not all) companies in the world are continuing to apply more and more lean manufacturing concepts to their operations in order to be competitive. As discussed earlier, lean manufacturing encourages the reduction in both lead times and inventory levels. Inventory is considered waste, or muda. Significant increases in inventory are never the way to go. According to lean, companies must seek ways to improve lead time and customer service levels without dramatically increasing the inventory levels and therefore the cost associated with holding inventory. However, the TMX operation is focused on acting as a middleman. Through this operation, Boeing eats up all the risk on its end in order to improve service levels from their suppliers. In order to do this, Boeing must convert a relatively fixed lead time into a much shorter lead time (by acting as a supermarket or retail outlet for the suppliers) and stabilize prices. This project utilized a wide assortment of research about retail store stocking policies/inventory management, service levels, and lead times as an aid for designing and analyzing the system between the metal mills, Boeing Commercial Airplanes, TMX Aerospace, and Boeing's suppliers.

## Design

As a refresher, the specific intended methodology followed for this project is summarized below:

1. Examine any actual data supplied by Boeing
2. Generate test data for the project
3. Design the replenishment system as a test platform and eventually as a basis for conducting additional analysis
4. Verify designed system with project stakeholders
5. Conduct analysis on designed system
6. Report results

In reality, the most basic considerations for designing the system are discussed in this "Design" section. This section also serves to develop a feeling for the kind of data that needs to be generated for the analysis of the system. As will be explained later, further explanation of how the system was designed continues into the "Experimentation" section. The reason for this is that these concepts are best illustrated through examples. In fact, the experimentation process is what confirmed or challenged the initial ideas and molded them into the designed system. As for the generation of test data, this was done on the fly and as such will also be discussed in the "Experimentation" section. In addition, the analysis of the system will also be explained in the "Experimentation" section, making it the busiest section of this report.

To kick-start the actual project at Boeing, only one specific type of metal (commodity) will be examined at a time. The reason for this is that although the demand

for individual commodities is not entirely independent of one another, the relationships between them are also very complicated. It would be difficult to logically group them together and accurately model their demand. With this being said, the design phase of this senior project will use aggregate data (data summarized to represent all commodity types). This data will be used to build and test the proposed system. Once the system has been confirmed, data from each individual commodity will be fed into the system in order to obtain the desired outputs.

At this point, it is apparent that there will be the added difficulty of the verification process. Like mentioned before, Boeing and TMX do not have a well-structured replenishment system for the metal distribution strategy at this point in time. Therefore, there is no benchmark for this system to be tested against. The system must be developed from past data and continue to be tested and monitored for future replenishment cycles. Adjustments will need to be made to improve the system and reach the desired service level.

To begin, it is important to consider the type of analysis that this project is intended to provide at the very end. Once again, this project is meant to expose the difference in costs between operating what Boeing calls the “TMX Crossdock” operation and a more traditional method of aggregation. More importantly, the project will also reveal the increased costs that Boeing picks up from running this service for its suppliers. Eventually, these costs will be weighed against the benefits that the service provides to Boeing, to Boeing’s suppliers, and basically anyone involved. However, quantifying these benefits is not within the scope of this particular project.

In order to conduct the analysis mentioned above, there needs to be a platform from which a sensitivity analysis can be performed. This platform will be built up from calculations ultimately involving the appropriate materials handling costs. The beginning point of this platform is the formula for total cost shown below:

$$Total\ Annual\ Cost = CD + \left(\frac{D}{Q}\right)S + \left(\frac{Q}{2}\right)hC$$

where C = material cost/unit (lbs.), D = annual demand, Q = lot size, S = ordering cost, h = holding cost as a percentage of material cost

CD represents the total annual material cost. The aggregation strategy that Boeing coordinates through TMX does involve differences in pricing such as quantity discounts but these aspects are not the concern of the project. As such, this aspect of total annual cost will be ignored. (D/Q)S represents the total annual ordering cost and (Q/2)hC represents the total annual holding cost. These last two costs will be the focus of this project.

The annual holding cost will be examined first. The problem at hand can be thought of as a modified version of the traditional replenishment problem with ROP and EOQ. However, the modified version must now take into account the lead time differences and customer ordering variance.

In actuality, very little of the ROP and EOQ replenishment remains after modification. The main element retained is the jagged tooth structure shown in **Figure D-1** below. The largest cause of the shift away from this traditional replenishment system is the variation in demand within and between periods. The traditional system is based on constant demand. Because of this, EOQ will be considered but not act as a

fixed ordering amount (in **Figure D-1**, EOQ is shown as Economic Lot Size). EOQ is the optimal ordering amount after weighing the fixed ordering cost against the per unit inventory holding cost. EOQ is also based off of the assumption that an order placed in a cycle will be received at the beginning of the next cycle and consumed in that cycle. This is not the case in this situation because of the excessive lead times in supply. As will be explained in the paragraph about the lead time issue and how it relates to ROP, this is not a feasible option. This replenishment system is beginning to shape up into more of a periodic review situation instead of the traditional continuous review scenario.

The lead time issue is huge and is also the main focus of this paper. It changes everything. In order to reduce the lead time to about 10% of its original value, the concepts of ROP must actually be abandoned altogether. If Boeing were to wait until the inventory dropped to a certain point to place an order, the warehouse would be forced to carry a ridiculous amount of inventory. The warehouse would be required to hold AT LEAST as much inventory as the average demand for the lead time period which means that the warehouse would need to hold the average demand over 40 weeks, for every commodity type. **Figure D-1** illustrates this concept. Most likely, the EOQ will be much less than the value of average demand for 40 weeks. In that scenario, the lot size will be pushed to the 40 week demand and the system will be suboptimal. Essentially, once an order is received, another order must be placed. The revised figure depicting this new replenishment scenario is shown in **Figure D-2**.

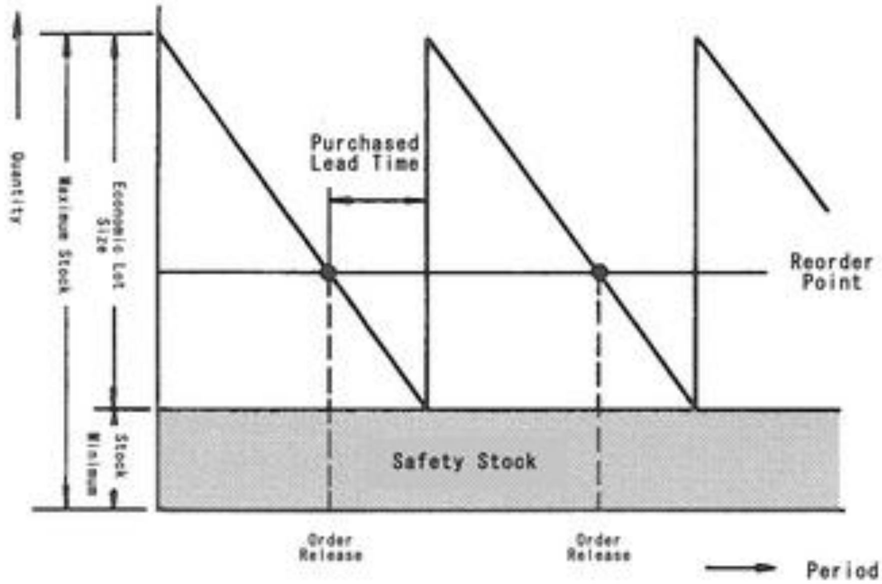


**Figure D-1.** Traditional replenishment cycle with EOQ and ROP[1]

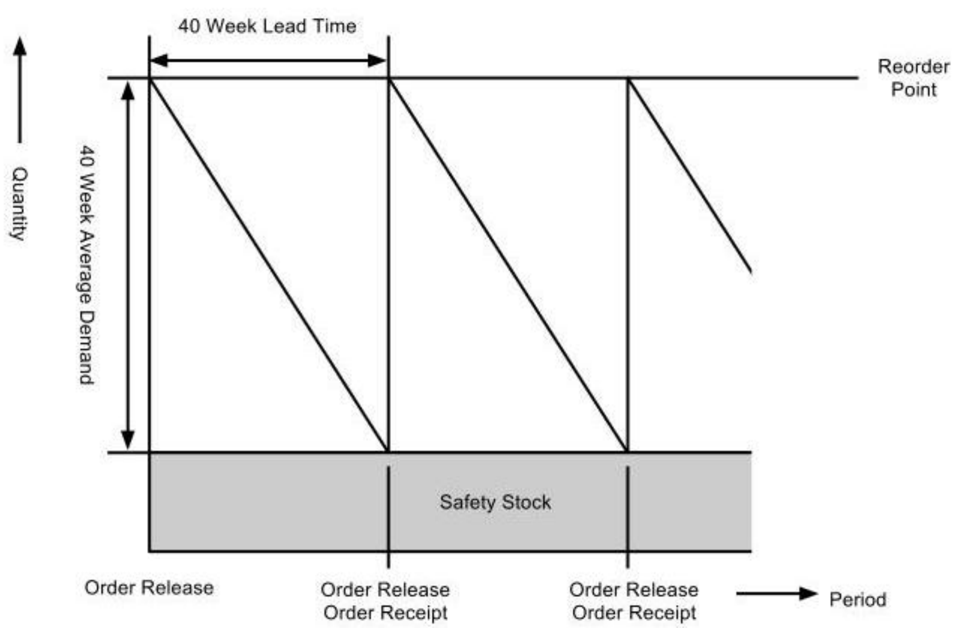


**Figure D-2.** Revised replenishment cycles with order quantity = 40 week average demand

1 http://www.asprova.jp/mrp/glossary/en/index/f/post-661.html

Now the question becomes whether this system could be revised and pushed even further. The answer is that it can. In order to do this, the ROP must now be abandoned as mentioned earlier. The system will no longer wait until the inventory levels reach a predetermined point to place another order. Instead, the system will place more weight on the forecasts provided. In the traditional ROP/EOQ system, the time between order releases is never less than the lead time of supply. In the extreme case shown in **Figure D-2**, the time between orders was equal to supply lead time but did not go past that. In the new system, the decisions of when orders are placed and how much to order are based upon the forecast of customer demand in predetermined intervals. There will be orders arriving at the beginning of each interval to satisfy the demand during that interval. However, unlike the traditional case, that order will have been placed many intervals before based on the forecast. Due to this fact, the forecasts must be fairly accurate. In order to offset the risk surrounding these forecasts, extra inventory must be held in the form of safety stocks.

Safety stock inventory is necessary due in part to the variation in customer demand as mentioned in the preceding paragraph. However, in this case, the performance of the supply stream also plays a part in increasing the amount of safety stock that needs to be held. The metal mills that supply the warehouses are not perfect. The contracts specify a 40 week lead time and a certain amount of metal to be delivered but the mills do not meet the contracts 100% of the time. There are times when the entire shipment is late and there are times when a partial shipment is on time but part

of the shipment did not make it in time. In this project, any of those two situations would be counted as not meeting the requirements.

Just for the sake of discussion, both demand from the customers (the internal and external suppliers) and the supply from the mills are assumed to follow normal distributions. (Note: Technically speaking, only data from the population are considered to follow a "distribution." The same cannot be claimed for samples. However, the word "distribution" will be used to describe samples in this project because it provides the best description for what the project is attempting to accomplish.) In reality, the data needs to be analyzed and tested to determine the proper fit of a distribution. In most cases, the normal distribution will be a good approximation. When examining normal distributions, the variable in consideration will produce a mean value $\mu$. This will be the value in the forecast that the system will plan around and "aim for." In the case of demand, whenever the actual demand is higher than the forecasted number, there will be a shortage. In the case of supply, whenever the supply is lower than the planned number, there will be a shortage. **Figure D-3** graphically displays the distribution and service level for demand and **Figure D-4** does the same thing for supply.

At this point, it is important to reiterate that the mean values for demand are the expected values. Just from examining these expected values, the advantage stated earlier becomes clear. The warehouse is only required to hold as much as inventory as it is expected to consume within the specified order periods (4 week intervals in this example) plus safety stock instead of consumption over the supply/replenishment lead time (40 weeks in this example). Ideally, the length of the intervals should be chosen so

that the order amount is close to the economic order quantity (EOQ) for a majority of the time. On the other hand, the risk calculations are also different for both situations. This means that the safety stock levels are different for each case. This difference between the safety stock levels will be one of the desired outputs of the model.

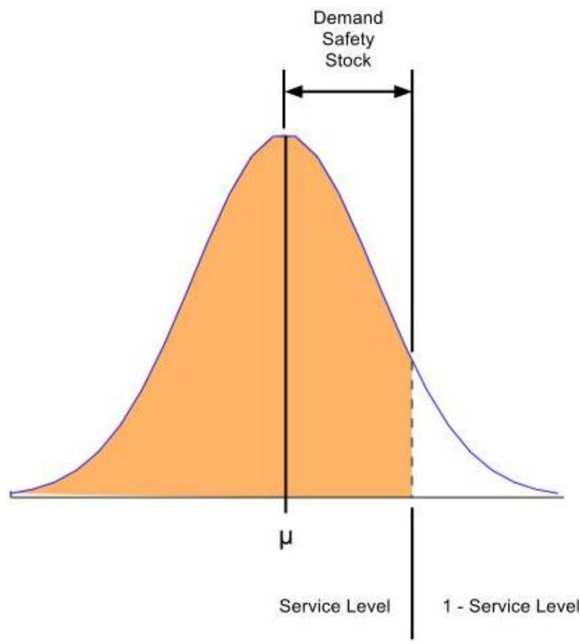


**Figure D-3.** Normal distribution for demand

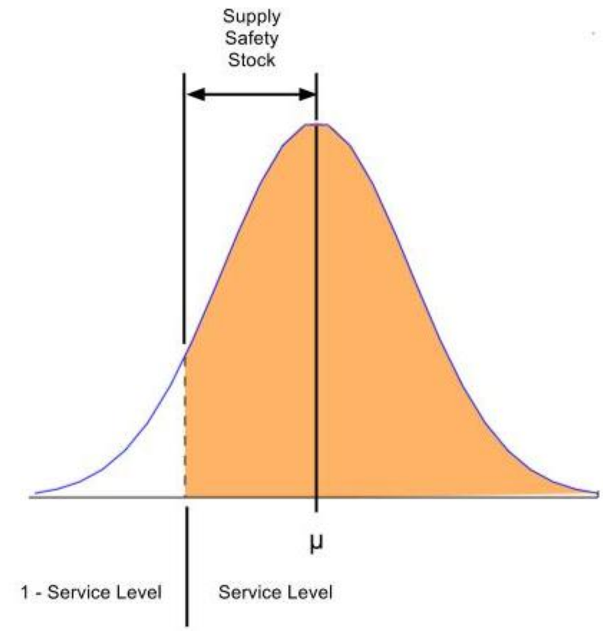


**Figure D-4.** Normal distribution for supply

$$\mu_D = Mean\ of\ Demand$$

$$\mu_S = Mean\ of\ Supply$$

$$SS_D = Safety\ Stock\ Due\ To\ Demand\ Variations$$

$$SS_S = Safety\ Stock\ Due\ To\ Supply\ Variations$$

$$SL_W = Service\ Level\ at\ the\ Warehouses$$

In order to figure out the amount of safety stock held due to demand variations, a service level must be set. The service level referred to in the demand issue is the service level required for the TMX warehouses ($SL_W$). Once the desired $SL_W$ is determined, this value will be used to calculate the corresponding customer demand level. From this point on, this customer demand level will be symbolized by $D_{max}$. In the case of demand, this value will be higher than the mean. In practice, if the actual

customer demand for that interval of time is less than or equal to $\mu_D$, the planned inventory will be sufficient for satisfying the orders. If the actual customer demand is between $\mu_D$ and $D_{max}$, the warehouse will rely not only the planned inventory but must also dip into safety stock to satisfy the orders. Finally, if the actual customer demand is greater than $D_{max}$, even the combination of planned inventory and safety stock will be unable to satisfy all orders. The amount of safety stock that is held is calculated by subtracting the mean from $D_{max}$ as shown in the equation below.

$$SS_D = D_{max} - \mu_D$$

$$SS_D = F^{-1}(SL_W, \mu_D, \sigma_D) - \mu_D$$

It just so happens that calculating safety stock due to supply is not as easy as it is for demand. Mill performance information isn't supplied in the form of lbs. Instead, examples of the information provided are the amount of late shipments and the number of days late. The goal is to somehow translate this information into an inventory measure such as weight in lbs. That information can then be graphed like in **Figure D-4.** This aspect will currently be looked over in this project and left as a point for improvement. Converting the provided mill performance information into the useful distribution of lbs is a difficult task but once it is completed, that information can easily be entered into the model. For this project, the distribution of supply will be arbitrarily selected after inspection of the provided information.

After the above was stated, the search was on for an adequate approximation of mill performance that can be easily converted into an amount of safety stock held. After much deliberation and consideration of the mill performance data that can be obtained,

a heuristic solution was defined. This solution involves compiling all relevant order information regarding the amount of orders that were late and the amount of days that the orders were late. All of this information will be based on historical data about all of the mills that supply the specific commodity in question. This information will be used to compile a histogram and a frequency chart with probabilities and cumulative probabilities. From these cumulative probabilities, a value near or slightly above the desired TMX service level will be identified. The amount of days late corresponding to this probability will be the bound on the amount of days late that are covered with the supply side safety stock. The calculation for the supply side safety stock level is formulated below. It is clear at this point that the mill service level alone is not enough information to perform these calculations. The provided information must dig deeper into the data that is used to calculate the mill service levels.

$$B = bound\ on\ amount\ of\ days\ late\ to\ be\ covered\ by\ supply\ side\ safety\ stock$$

This bound amount is associated with the desired service level from TMX.

$$P_i = probability\ of\ i\ amount\ of\ days\ late$$

$$DL_i = i = amount\ of\ days\ late$$

$$SS_S = \sum_{i=0}^{B} \mu_D \times P_i \times DL_i$$

Each i in this equation corresponds to an incremental amount of days late. The summation begins with an i=0 which means that the order is not late and increments up until the designated bound value.

$$SS_{total} = SS_D + SS_S$$

Once all of the safety stock levels have been calculated, they are combined with the planned inventory levels. The task now becomes maintaining these levels by planning the correct amount of inventory to arrive at the beginning of each interval. The first step is to determine the length of this time interval. Optimally, the interval will be chosen so that the order sizes for each interval will correspond to the EOQ value. In this project, the orders will need to be planned 40 weeks out. The new question is whether the safety stock $SS_{total}$ will be able to hold out for 40 weeks at the service level stated ($SL_W$). Typically service levels guarantee that say SL = 95% of the time, the next order will be completed successfully. However, if the SS is depleted during that cycle, the amount depleted will need to be added to the next order so that it can be refilled. However, since the supply lead time is 40 weeks, the safety stock replenishment order might be several cycles out. For example, if the time interval was chosen to be 4 weeks, after the order has been placed to replenish the safety stock, 10 cycles would pass before the order arrives. In this case, the actual service level is $(95\%)^{10} = 59.87\%$ which is much less than what was intended and definitely unsatisfactory. This lower service level is due to the fact that the same amount of safety stock is covering risk for multiple periods when it was calculated to only cover one period.

Now the following is known: the amount of safety stock that needs to be held in each period in order to achieve a certain service level (95% in this example). With this information, how can the aggregate amount of safety stock that needs to be held at any point in time be determined? Once again, the individual safety stock amount for a single period is not adequate to cover risk because there are predetermined order points and

a long replenishment lead time. The formula for the estimate of the amount of risk that needs to be covered at any point in time in terms of time is shown below.

$$LT_S = Observed\ Lead\ Time\ from\ the\ Mills\ at\ the\ Warehouses,$$
$$Supply/Replenishment\ Lead\ Time$$

$$LT_D = Observed\ Lead\ Time\ from\ the\ Warehouses\ at\ the\ Customers,$$
$$Demand/TMX\ Lead\ Time$$

$$I_O = Length\ of\ Ordering\ Intervals$$

$$Risk\ (in\ terms\ of\ time) = LT_S - LT_D + I_O$$

This risk can be broken down into two categories: 1) the risk resulting from the length of the order interval, $I_o$ and 2) the risk resulting from the offered lead time to the customer, $LT_S - LT_D$. **Figure D-6** below illustrates this concept visually. It becomes obvious at this point that risk has a positive relationship with the length of the order interval (as the length of the order interval increases, so does the risk) and a negative relationship with demand LT (as demand LT decreases, risk increases).

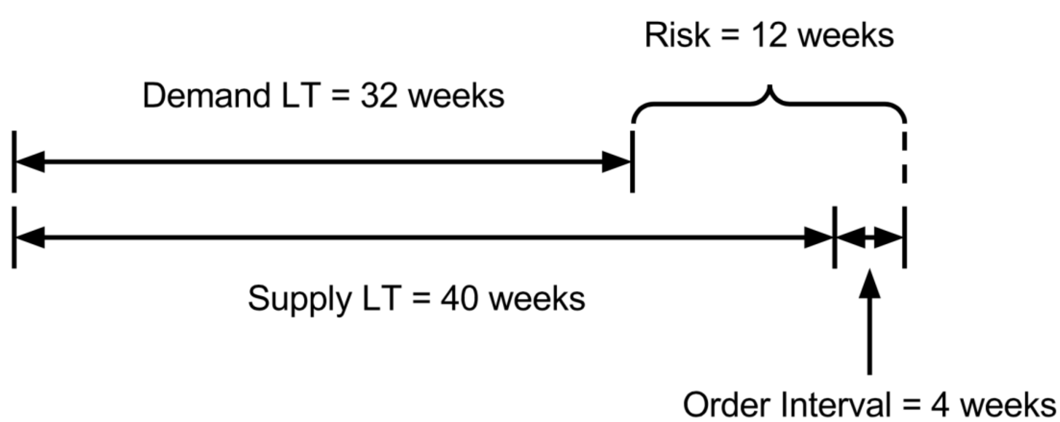


**Figure D-6.** Risk (in terms of time) diagram

Some additional topics are best explained through examples and that is exactly what will happen. The next section discusses the experimentation process where the concepts explained in this section are put to the test.

## Experimentation

Example 1:

To initiate the experimentation process, a simple example is considered. This example will only involve a safety stock due to demand variations or the variation from customer orders. The following parameters were used to represent data pertaining to a single commodity, aluminum plate. This means that the information in this example will aggregate all customer demand of aluminum plate. Parameters: Mill SL = 0.9, TMX SL = 0.95, Mill LT ($LT_S$) = 40 weeks, TMX LT ($LT_D$) = 4 weeks, Order Interval (OI) = 4 weeks, the demand distributions for each period all follow N(10,000, 700) lbs. The succeeding discussion can be referenced to the Excel snapshots, **Appendix A-1** and **Appendix A-2**. First, the risk that must be covered in terms of weeks is equal to 40 – 4 + 4 = 40. This translates to 10 periods since the order intervals are set at 4 weeks. The current period is known as period 1. The risk for periods 2 through 11 must be covered. The proposed system of placing multiple orders within the supply LT based on forecasts is analyzed first. The safety stock amounts (only $SS_D$ in this example) for these periods are calculated using =NORMINV(TMX SL, mean, stddev) in Excel. Since all of these periods follow the same distribution, they all have the same safety stock amount of 1,151.40 lbs. The total safety stock ($SS_T$) is equal to 11,513.98 lbs. Note: Multiplying 1,151.40 by 10 will not result in the $SS_T$ value because 1,151.40 is a rounded value and the actual value is used in the calculations. Now, an assumption is made that over the course of a period, on average, TMX will hold as much inventory as the starting amount divided by 2. So in this example, TMX will hold 5,000 lbs of normal inventory on average (this value is also

known as the cycle inventory). Adding the safety stock to this will yield a total inventory level of 16,513.98 lbs on average.

Analysis is now performed on the traditional ROP situation where TMX must hold at least as much inventory as demand during the supply LT. Combining the demand distributions from each of the periods from period 2 through period 11 results in N(100,000, 2,213.59) lbs. This is done using concepts within arithmetic of random variables. From this, the same normal probability calculation is performed and results in a safety stock amount of 3.641.04 lbs. This calculates to a total inventory level of 53,641.04 lbs. The gap (the difference between the inventory held in the traditional system and that held in the proposed system which signifies the advantage of using the proposed system over the traditional system) is equal to 37,127.06 lbs. The tradeoff here is between the cycle inventory and the safety stock levels. The proposed system carries more risk and therefore must carry slightly more safety stock even when the supply-side safety stocks are left out. However, this is more than made up by the fact that the proposed method significantly reduces the cycle inventory that the system works with. The proposed system introduces an extra 7,872.94 lbs of safety stock in order to reduce cycle inventory by 45,000 lbs. This is what creates the gap. The following are examples of the considerations that should be taken into account: 1) For the proposed system, the warehouse only needs to allocate enough storage space for around 10,000 lbs of the commodity and will only carry 5,000 lbs of the commodity on average. Compare this to the space necessary to store 100,000 lbs of the commodity and the average holding of 50,000 lbs of the commodity in the traditional system. This

will significantly reduce holding costs. 2) Ordering costs might be significantly higher for the proposed method. Transportation costs might be increased since orders must be delivered 10 times as often as in the traditional method. Quantity discounts may not be realized if the smaller orders are placed. There are equations to calculate EOQ that takes these factors into consideration. Once again, EOQ should be calculated in this manner. This EOQ value will then be used to determine the optimal order intervals with respect to demand. One reason that BCA is more concerned with the first point is that the system is able to leverage the size of this system and economies of scale to negate the effects of the second point. In addition, there are many available formulas that will account for ordering costs and quantity discounts into the calculation of EOQ. Since EOQ will be factored into the design of the system, the bases will be covered.

$$Gap = Difference\ in\ TOTAL\ inventory\ between\ the\ traditional\ system\ and\ proposed\ system$$

Summary (Scenario 1):

$$Safety\ Stock\ of\ Proposed\ System = 11{,}513.98\ lbs$$

$$Total\ Inventory\ of\ Proposed\ System = 16{,}513.98\ lbs$$

$$Total\ Inventory\ of\ Traditional\ System = 53{,}641.04\ lbs$$

$$Gap = 37{,}127.06\ lbs$$

The following is an example of how the EOQ calculation can be used to determine an optimal ordering interval. Since there has already been a lot of work concerning the calculation of EOQ under various situations, EOQ will simply be assumed

to be 10,000 lbs. If demand averages 20,000 lbs/month, orders will be placed twice a month. It is as simple as that once the EOQ has been calculated.

The next step is to consider the effects of altering the values of the variables of interest. For example, the lead time to the customer or the TMX LT ($LT_D$) is changed from 4 weeks to 8 weeks. What this does is alter the amount of risk that must be covered by the safety stock in terms of weeks. This risk is equal to 40 – 8 + 4 = 36 weeks. The same calculations as explained above are performed and a summary of the results is shown below.

Summary (Scenario 2):

$$Safety\ Stock\ of\ Proposed\ System = 10{,}362.58\ lbs$$

$Total\ Inventory\ of\ Proposed\ System$ = 15,362.58 lbs

$$Total\ Inventory\ of\ Traditional\ System = 53{,}641.04$$

$$Gap = 38{,}278.46$$

The most obvious observation is that the total inventory of the proposed system is reduced between scenario 1 and scenario 2. This is because there is less system risk in scenario 2 than in scenario 1 (9 periods vs. 10 periods). It is also important to point out the fact that the inventory for the traditional system remains unchanged despite the altered values. This results from the fact that the order interval for the traditional system essentially remains at 40 weeks or 10 periods in this case. Also, the differences between lead time from the mill and lead time to the customer do not affect the system. Therefore, the traditional system is consistently dealing with 10 periods of risk for this example.

Another key point is that since the total inventory of the traditional system is constant, any decreases in the total inventory of the proposed system will directly lead to an increase in the gap. This is a very intuitive situation. The desirable situation is for a decreased amount of total inventory and that will be represented by an increased gap. In this example, the gap increased between scenario 1 and scenario 2. In fact, the next step would be to examine the most extreme situation in which there is no risk to be covered. This is the situation where lead time from the mill is equal to lead time to the customer and the order interval is 0 (orders may be placed at any time, single orders are allowed). In this situation, the total inventory of the proposed system will be 0 since no risk needs to be covered. Once again, the essential order interval for the traditional system is still 10 periods due to how it operates. Therefore, the total inventory of the traditional system still remains the same at 53,641.04. This is the maximum gap possible for this situation. The takeaway from this analysis is that 1) as the 2 lead times (from the mill and to the customer) converge, it becomes more important to use the proposed system over the traditional system[2] and 2) as the order interval approaches 0, it becomes more important to use the proposed system over the traditional system.

Regardless, this example has shown that the proposed system is much more desirable than the traditional system. However, the claim that there is a possibility of zero risk, even theoretically, is troubling. The reason that this is possible is due to the fact that the uncertainty from supply has not been accounted for. It is possible to reduce uncertainty from demand to practically zero but it is not possible to do the same for

uncertainty from supply. The next example will examine the effects of uncertainty in supply.

Example 2:

This next example will introduce a new element to the situation in example 1. The first scenario of example 1 will be considered first and then the results of the second scenario will be revealed as well. Mill performance will be incorporated into the model and will effectively increase the amount of safety stock that will need to be held. Like in Example 1, all of the mill performance data that are fabricated for this example represent compiled information for all mills that provide aluminum plate to TMX. This fact must be kept consistent for an accurate analysis. A snapshot of the data used in this example is shown in **Table E-1** below. Currently, this data has no real-life implications and is completely made up. Like in the data for example 1, actual data will need to be converted into this format for useful results.

**Table E-1.** Snapshot of data for example 2

| Days Late | Count |
|---|---|
| 0 | 900 |
| 1 | 20 |
| 2 | 15 |
| 3 | 10 |
| 4 | 6 |
| 5 | 7 |
| 6 | 7 |
| 7 | 7 |
| 8 | 4 |
| 9 | 4 |
| 10 | 2 |
| 11 | 1 |
| 12 | 3 |
| 13 | 1 |
| 15 | 1 |
| 18 | 1 |
| 19 | 1 |
| 20 | 1 |
| 27 | 1 |
| 30 | 2 |
| 32 | 1 |
| 33 | 1 |
| 38 | 2 |
| 50 | 1 |
| 99 | 1 |
| Total | 1000 |

As an example to illustrate the information that this table represents, there are 1,000 total orders and 100 of them were late. This represents an overall average mill service

level of 90%. Of those late orders, 20 of them were 1 day late. Plotting this information in JMP as a distribution will reveal the cumulative probabilities at each amount of days late. The JMP output is shown below in **Figure E-2**. From these cumulative probabilities, it is clear that at a 95% service level for TMX, the safety stock must account for an amount of up to 4 days late.

| Days Late | Count | Prob | Cum Prob |
|---|---|---|---|
| 0 | 900 | 0.90000 | 0.90000 |
| 1 | 20 | 0.02000 | 0.92000 |
| 2 | 15 | 0.01500 | 0.93500 |
| 3 | 10 | 0.01000 | 0.94500 |
| 4 | 6 | 0.00600 | 0.95100 |
| 5 | 7 | 0.00700 | 0.95800 |
| 6 | 7 | 0.00700 | 0.96500 |
| 7 | 7 | 0.00700 | 0.97200 |
| 8 | 4 | 0.00400 | 0.97600 |
| 9 | 4 | 0.00400 | 0.98000 |
| 10 | 2 | 0.00200 | 0.98200 |
| 11 | 1 | 0.00100 | 0.98300 |
| 12 | 3 | 0.00300 | 0.98600 |
| 13 | 1 | 0.00100 | 0.98700 |
| 15 | 1 | 0.00100 | 0.98800 |
| 18 | 1 | 0.00100 | 0.98900 |
| 19 | 1 | 0.00100 | 0.99000 |
| 20 | 1 | 0.00100 | 0.99100 |
| 27 | 1 | 0.00100 | 0.99200 |
| 30 | 2 | 0.00200 | 0.99400 |
| 32 | 1 | 0.00100 | 0.99500 |
| 33 | 1 | 0.00100 | 0.99600 |
| 38 | 2 | 0.00200 | 0.99800 |
| 50 | 1 | 0.00100 | 0.99900 |
| 99 | 1 | 0.00100 | 1.00000 |
| Total | 1000 | 1.00000 | 1.00000 |

**Figure E-2.** Probabilities for example 2 in JMP

The next step is to calculate the amount of safety stock that must be held for each amount of days late up to the 95% TMX service level value of 4 days. To do this, the following equation is used for each level of days late:

$$SS_S = Demand \times P_{DL} \times DL$$

$$P_{DL} = Probability\ of\ DL\ Days\ Late$$

$$DL = Days\ Late$$

In the example, average demand per period is used. In practice, a more exact calculation would use the actual demand for each period. This would cause the required amount of $SS_S$ to fluctuate and this is consistent with real life situations. In Example 2, the safety stock due to supply variations is equal to 1,040 lbs (detailed in **Appendix A-5**). This is added to each period and the results are shown in **Appendices A-3 (for Scenario 1) and A-4 (for Scenario 2)**. The safety stocks due to supply variations in this example are huge. They are nearly as large as the demand-side safety stocks and effectively, the total inventory that must be held during the current period is about 63% more than in example 1.

An extra step must be taken to calculate the safety stock due to supply variations for the traditional method. Once again the mean of demand is 100,000 lbs and the standard deviation of demand is 2,213.59 lbs. With these values, the demand-side safety stock can be calculated. The same principles just mentioned are used to calculate the supply-side safety stock. The total demand for the period of 40 weeks is used. This results in the enormous value of 10,400 lbs. This number is significantly larger than the

demand-side value (about 186% more). The total inventory that must be held for the current period is 64,041.04 lbs.

Summary (Scenario 1):

$$Safety\ Stock\ of\ Proposed\ System = 21{,}913.98\ lbs$$

$$Total\ Inventory\ of\ Proposed\ System = 26{,}913.98\ lbs$$

$$Total\ Inventory\ of\ Traditional\ System = 64{,}041.04\ lbs$$

$$Gap = 37{,}127.06\ lbs$$

Summary (Scenario 2):

$$Safety\ Stock\ of\ Proposed\ System = 19{,}722.58\ lbs$$

$$Total\ Inventory\ of\ Proposed\ System = 24{,}722.58\ lbs$$

$$Total\ Inventory\ of\ Traditional\ System = 64{,}041.04\ lbs$$

$$Gap = 39{,}318.46\ lbs$$

An interesting point to examine is the fact that the safety stock due to supply variations is the same for both the proposed method and the traditional method. This adds to the discussion in example 1 about the gap between the two methods. In example 1, only demand-side variations were examined and it was said that reducing the effective risk period would increase the gap. The addition of supply-side safety stocks amplifies this effect. The takeaway from this discussion is that the gap grows at an increased rate between the traditional method and proposed method and it is now even more important to use the proposed method over the traditional method. The reason for this is that while the traditional method is fixed in the amount of inventory it

is required to hold, reducing the risk period calculated also reduces the amount of inventory that is required to be held for the proposed method.

This example actually identifies a loophole in the current design of the system. Under the scenario where $LT_S = LT_D$ and orders can be placed at any time, the proposed system would suggest that no risk needs to be covered and this does not seem correct by any means. It was said that if $LT_S = LT_D$ and if orders can be placed at any time, there would be no need for demand-side safety stocks (for the proposed system). The required amount of inventory would be equal to the cycle inventory and the gap between methods will always be the total inventory level of the traditional system minus the cycle inventory of the proposed system. Even in this scenario, orders may still be late on the supply side. Supply side risks will always be lurking around and this system should reflect this fact. The best solution for this is to dictate that at the very least, there will be one period of supply-side risk. So for this example, even if the effective risk period is deemed to be zero ordering periods, there will still be a safety stock of 1,040 lbs.

Example 3:

Now that both demand uncertainty and supply uncertainty have been incorporated into the replenishment system, the total costs can be examined. To start, the typical holding cost for this kind of material is 20% of the material cost and this is the holding cost that will be used for this example.

$$h = 20\%$$

$$Cost\ of\ aluminum\ plate/lb, C = \$2$$

$$Fixed\ transportation\ and\ holding\ costs, S = \$5{,}000$$

Once again, the equation for total cost that this project this is based off is show below.

$$Total\ Annual\ Cost = CD + \left(\frac{D}{Q}\right)S + \left(\frac{Q}{2}\right)hC$$

The ordering quantity, Q, that all of the previous examples have been using is 10,000 lbs. The total annual material cost is only important to include in a comparison that involves quantity discounts. The term for total annual holding cost also fails to represent the amount of safety stock that must be held. The cycle inventory Q/2 will be replaced by the total inventory calculated in our previous examples and will be represented by $I_T$.

$$Total\ Annual\ Cost = CD + \left(\frac{D}{Q}\right)S + I_T hC$$

$$Total\ Annual\ Cost\ (Scenario\ 1) = \$335{,}765.59$$

$$Total\ Annual\ Cost\ (Scenario\ 2) = \$334{,}889.03$$

The entire Excel analysis can be seen in **Appendix A-6**, but the only term that was different is the holding cost. As mentioned before, scenario two poses a smaller risk and therefore requires a smaller amount of safety stock inventory and total inventory. Correspondingly, the total annual cost of operating the system is lower for scenario 2. To address another difference, the “traditional method” of replenishment was also evaluated. This traditional counterpart to scenario 1 essentially involves ordering in larger quantities and holding more inventories as a result. Once again, refer to the Appendix for the detailed results. As expected, the ordering costs were decreased and the holding costs were increased. Ultimately, this traditional method was actually

cheaper for this specific example due to the low product cost and high fixed ordering costs.

$$Total\ Annual\ Cost\ (Scenario\ 1\ Traditional) = \$292{,}116.42$$

Example 4:

An all unit quantity discount will be incorporated into this example. This quantity discount will serve two purposes. First, the addition will show how quantity discounts affect the total costs of the replenishment system. Second, the calculated optimal lot size resulting from the quantity discount will exemplify how optimal lot sizes (EOQ or Q*) are used to determine the planning periods. The pricing structure for the all unit quantity discount is shown below. Once again, this will help to demonstrate how optimal order quantities should be used in coordinating a replenishment strategy.

**Table E-3.** Prices of all unit quantity discount

| Pounds of metal purchased | Price per lb. |
|---|---|
| 0 – 2,499 | $2 |
| 2,500 – 4,999 | $1.97 |
| 5,000 – 7,499 | $1.95 |
| 7,500+ | $1.9 |

The resulting optimal lot sizes for each price are shown below.

**Figure E-4.** Optimal order quantities as a result of all unit quantity discount

| lbs purchased | C | | | |
|---|---|---|---|---|
| 0 - 2,499 | 2 | | Q0 | 57,008.77 |
| 2,500 - 4,999 | 1.97 | | Q1 | 57,441.21 |
| 5,000 - 7,499 | 1.95 | | Q2 | 57,735.03 |
| 7,500+ | 1.9 | | Q3 | 58,489.77 |

Abiding by the rules for evaluating these order quantities, $Q_0$, $Q_1$, and $Q_2$ can be ignored. This leaves $Q_3$ as the only remaining possibility and makes it the optimal ordering quantity when considering the all unit quantity discount. The lot size of 58,489.77 lbs. is between the lot size of 10,000 lbs. for the proposed system in scenario 1 and the lot size of 100,000 lbs. for the traditional system. This should be kept in mind as the analysis is conducted. If the calculation for optimal order quantity is consistent with the design of this testing platform, the lot size of 58,489.77 lbs. should result in the lowest total annual cost. As can be seen in **Appendix A-7**, the TAC of the optimal situation is $280,884.35. In order to determine if this is in fact the lowest TAC, the quantity discount must be applied to the previous scenarios as well. The results of these calculations are shown in **Appendix A-8** and are also summarized below. The traditional system still ends up being slightly less costly than even the optimal situation. The reason for this is that the calculation of optimal order quantity does not factor in safety stocks and safety stocks have huge impacts in the contexts of this project. Another neglected and possibly important consideration is truck capacity. If truck capacity is exceeded and another truck must be hired to split the load, it may not be as beneficial to buy such large quantities. This is a very likely possibility considering the commodities of interest. Once again, this finding just comes to show that the extraordinarily high fixed ordering and transportation costs make it much better to buy in bulk and hold the inventory than to place additional orders. This proves the fact that the model is very sensitive to changes in certain factors.

$$Total\ Annual\ Cost\ (Scenario\ 1\ Optimal) = \$280{,}884.35$$

$$Total\ Annual\ Cost\ (Scenario\ 1\ Proposed) = \$335{,}765.59$$

$$Total\ Annual\ Cost\ (Scenario\ 1\ Traditional) = \$279{,}116.42$$

Note: An examination of **Appendix A-7** will show that the calculated risk for example 4 is 14.85 periods. For this example, 14.85 is close enough to be rounded to 15 periods for the sake of simplicity. For a more accurate analysis, it may be more beneficial to multiply the last period's safety stock inventories by the fraction (0.85 in this case). A sensitivity analysis will show that this does not make a big difference unless the risk periods considered are extremely low.

## Results

Now that the replenishment system has been designed and the testing platform has been completed, additional analysis can be completed at the company. At this point, it is important that I step into a first person explanation of the situation. Currently as a student on academic leave of absence from Boeing Commercial Airplanes, I was unable to readily access the data required since I am not considered an employee. The data described is located on multiple servers that all require specific permissions to access. In order to ensure that the main objectives of the project were met, the project stakeholders and I decided to proceed with fabricated data. Once I return to the company, I will be able to access the relevant data and convert either the model to work with the new data or to transform the data into the proper inputs for the created model. So far, the results have shown that the model is very sensitive to the factors of interest. The optimal replenishment system will depend very strongly on factors such as material cost, ordering and transportation cost, holding cost, and even factors that were not examined in this report such as truck capacity.

All of this leads to the main goal of this project: identifying the costs of the aggregation strategy and the lead time manipulation service that TMX provides. The reason that this cost is unclear is because there currently is no clear and defined replenishment system at TMX. Metal is being purchased at a contracted amount for a set price. As this is happening, TMX is attempting to burn through inventory that has been accumulated over time. Boeing eventually hopes to burn through this huge stockpile of inventory and implement a more lean replenishment system that

follows more of a “just in time” approach and is more dynamic. These cost calculations will serve many purposes, some of which are obvious and traditional. The purpose that is one of the most important is to allow the company to weigh the costs against the benefits. A purpose that is more unique is to identify to the Boeing suppliers that while they are benefiting from this operation, Boeing has invested a lot of money to start the strategy and that they are continuing to spend a lot of money to keep it running. Boeing hopes that this will help the suppliers understand that they should also contribute to the funding of this project that benefits everyone in the supply chain but is currently only funded by Boeing.

From what has just been stated, another next step may be to quantify the benefits that the aggregation strategy and lead time manipulation service provides. A selection of the most important benefits have been listed but assigning a dollar value to these benefits is much more difficult than estimating the costs of running the operation. However, doing so will truly demonstrate whether the aggregation strategy and lead time manipulation service are truly worth the effort. Being able to divide up the benefits into percentages will also aid in persuading the suppliers that they have a responsibility to contribute to the operation of the system.

Like mentioned earlier, the replenishment system used as a basis for this project is a rudimentary one that was constructed on the spot. It is rooted in basic industrial engineering principles with a huge emphasis placed on supply chain management. There is no doubt that there are more advanced solutions that may be able to provide more accurate results. Many of these solutions are incorporated into extremely useful supply chain management software packages. These packages will

definitely provide a genuine user-friendly interface that the replenishment system within this project is unable to provide. Whenever the warehouses operated by TMX Aerospace are able to transition to a more dynamic system (mainly a responsive replenishment system), it will be very beneficial for Boeing to consider these software packages for TMX. This is the situation that the analysis within this project has attempted to predict. Whenever Boeing and TMX are ready to make this transition, it will be very useful to compare the results of this project to the outputs of all the potential SC software. In this manner, the results of this study will aid in the selection of the proper software.

## Conclusion

This project is concerned with the costs of an aggregation strategy run by TMX Aerospace (on a contract with Boeing Commercial Airplanes) and the costs of performing lead time manipulation. The project stakeholders believe one of the largest benefits to the suppliers using the system is the reduction of perceived lead time by about a factor of ten. Currently, Boeing is single-handedly paying for the entire operation. Even so, they believe they are benefiting from this arrangement. Boeing is hoping to show their suppliers that they are benefitting from a system that Boeing is paying for on its own. Boeing hopes that this will improve their relationships with their suppliers and allow them to negotiate more favorable contracts with their suppliers.

There is currently no replenishment system at the warehouses operated by TMX because there are large stockpiles of inventory that have accumulated over time and are still continuously fed with new inventory. This is not the situation that Boeing planned from the start and therefore not a situation that Boeing wishes to stay in. Boeing is more interested in the details pertaining to a more idealized system where only very small amounts of inventory are held for small periods of time. In order to address the costs of this operation, a replenishment system must be decided upon. Therefore, the first step of this project is to create a simple replenishment system that is relevant to the specifics of the aggregation strategy and lead time manipulation service. This replenishment system will be built into an Excel template that will then be used as a platform for conducting sensitivity analysis. Factors such as the two lead times, mill performance, and order intervals

will be changed in order to observe their effects of total cost of operating the system. After tests were conducted on the model, the replenishment system was consistent with traditional notions of inventory behavior. The results also showed that the system is sensitive to the factors of relevance: mainly the lead times, the order interval, the material cost, the holding costs, and the ordering and transportation costs. The model is now ready for inputs of actual data from the company. This is the ultimate next step. It can be said that generalizations of the optimal replenishment system are hard to make and often inaccurate. Different situations require different methods of dealing with them. For this very reason, it is highly recommended that Boeing pursue the implementation of a supply chain management software package at TMX once this idealized situation has been reached (lead, just-in-time replenishment policy that is deemed optimal by calculations within the software). The replenishment system created for this project is very simple and will serve as a great resource for selecting an appropriate software package. However, it does have its limitations. One of these limitations is the lack of an intuitive user interface.

In the end, it is important for a company to analyze the effects of a project from a triple bottom line approach. Projects must balance the three aspects of the triple bottom line: people, planet, and profit. Of course, companies will always seek to improve their profit with their projects. This project is no exception. The main purpose of this project is to provide an analysis that will ultimately lead to the possibility of cost savings. These cost savings will create more profits for the company. The triple bottom line dictates that a company cannot mercilessly chase after profits with no regards to people and the planet. It is possible for a project to

improve multiple aspects with no detrimental changes to others and these would be the most beneficial projects. This project happens to be one of them. The ability for cost savings such as reduced storage costs will involve reduced consumption of resources, which is good for the planet. On the other hand, it was earlier mentioned that the proposed system might increase transportation costs. Trucks may need to make more trips in order to operate the proposed system. This is obviously going to be worse for the planet since it will cause more pollution and resource consumption. It is important for the system to recognize this and utilize the expansive operations it coordinates to maximize the productivity of the trucks. This means keeping the trucks as full as possible for each trip that it makes. This will likely require the combination of different commodities into a single shipment. Once this is done, the impact on the environment should not be any different than how it was before. In fact, in the grand scheme, the impacts on the environment will actually be reduced.

The impacts of this project will be felt less by people. There are no direct effects on the well being of people in general. The most influential foreseeable result has to do with the increased coordination required to operate the system. This might be counteracted by the reduction of resource consumption in the actual operations of the warehouse facilities. At the end of the day, no people are being mistreated as a result of this ongoing project. The benefit of a more stable supply chain can be seen as a benefit to everyone involved. All of the suppliers that purchase metal through this aggregation strategy benefit from the stable prices and the ability to order smaller amounts of metal at a time than they otherwise can. Boeing runs this service through TMX in order to hedge the risk so that their supply

chain upstream is as smooth and stable as possible. However, it has become obvious that the suppliers are also benefiting in terms of cost. This leads to another discussion that Boeing believes it needs to address. Boeing is running this system at a cost and the suppliers that use it are benefitting freely from the service. Boeing must decide if the suppliers should be required to start sharing the costs of operating the system. At the very least, Boeing should be able to use this fact as leverage in any future contract negotiations. Although there are less social benefits on an individual level, in an overall sense, society is left in a better place from the operation of this combined system of demand aggregation and lead time manipulation. Considering that the entire supply chain benefits from the system, all of the companies are more profitable than they were before. These improvements will likely trickle down to its employees and even to society outside of the supply chain. This project only considered the supply chain relationship from the metal mill up to Boeing. Due to the increasingly competitive nature of the commercial aircraft industry, these improvements will most definitely trickle down to the end customers (these being airlines and passengers and possibly even further). One may even go so far as to state that the benefits will force competitors to respond and improve their methods of conducting business as well.

Personally, I learned a great deal from working on this project. The literature review for this project was much more time-intensive and thorough than for any of my other works. During the process, I learned how to quickly assess the contents of a paper and determine if it was relevant towards my topic. During the research phase, much of the concepts that I was experimenting with were related to the field

of supply chain management. This was a natural consequence but I had yet to know it at the time. I had barely begun the class at Cal Poly (IME 417: Supply Chain and Logistics Management) as this project was nearing its end. I applied concepts from many of my previous classes in order to further the research I was performing in the field of supply chain analysis. Most notably, I used knowledge from my operations research classes for the ROP/EOQ calculations and strangely enough, my statistics applications were derived more from my quality control class (IME 430) than from my engineering statistics class (IME 326: Engineering Test Design and Analysis) but both were helpful. In addition, concepts from the following classes were also a tremendous aid: IME 223: Process Improvement Fundamentals, IME 410: Inventory Control Systems, IME 420: Simulation, IME 443: Facilities Planning and Design.

# Appendix

## Example 1

| Mill SL | TMX SL | | Mill LT (LTS) | TMX LT (LTD) | OI | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.9 | 0.95 | | 40 | 4 | 4 | | | | | | | |
| | | | | | | | | | | | | |
| Period | Demand Distributions | | | | | | | | | | | |
| | Mean | Std Dev | SSD | | SST | Total Inv | | Mean | Std Dev | | SST | Total Inv |
| 1 | 10,000.00 | 700.00 | 1,151.40 | | 11,513.98 | 16,513.98 | | 100,000.00 | 2,213.59 | | 3,641.04 | 53,641.04 |
| 2 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 3 | 10,000.00 | 700.00 | 1,151.40 | | Gap | 37,127.06 | | | | | | |
| 4 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 5 | 10,000.00 | 700.00 | 1,151.40 | | Dif SS | Dif Cycle Inv | | | | | | |
| 6 | 10,000.00 | 700.00 | 1,151.40 | | 7,872.94 | 45,000.00 | | | | | | |
| 7 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 8 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 9 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 10 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 11 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 12 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 13 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 14 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 15 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 16 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 17 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 18 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 19 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 20 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |

**A-1.** Excel snapshot of example 1, scenario 1

| Mill SL | TMX SL | | Mill LT (LTS) | TMX LT (LTD) | OI | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.9 | 0.95 | | 40 | 8 | 4 | | | | | | | |
| | | | | | | | | | | | | |
| Period | Demand Distributions | | | | | | | | | | | |
| | Mean | Std Dev | SSD | | SST | Total Inv | | Mean | Std Dev | | SST | Total Inv |
| 1 | 10,000.00 | 700.00 | 1,151.40 | | 10,362.58 | 15,362.58 | | 100,000.00 | 2,213.59 | | 3,641.04 | 53,641.04 |
| 2 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 3 | 10,000.00 | 700.00 | 1,151.40 | | Gap | 38,278.46 | | | | | | |
| 4 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 5 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 6 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 7 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 8 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 9 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 10 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 11 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 12 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 13 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 14 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 15 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 16 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 17 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 18 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 19 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |
| 20 | 10,000.00 | 700.00 | 1,151.40 | | | | | | | | | |

**A-2.** Excel snapshot of example 1, scenario 2

## Example 2

| Mill SL | TMX SL | | Mill LT (LTS) | TMX LT (LTD) | OI | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.9 | 0.95 | | 40 | 4 | 4 | | | | | | | | |
| Period | Demand Distributions | | | | | | | | | | | | |
| | Mean | Std Dev | SSD | SSS | | SST | Total Inv | | Mean | Std Dev | | SST | Total Inv |
| 1 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | 21,913.98 | 26,913.98 | | 100,000.00 | 2,213.59 | | 14,041.04 | 64,041.04 |
| 2 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 3 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | Gap | 37,127.06 | | | | | | |
| 4 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 5 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | 0.62976944 | | | | | | |
| 6 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | 2.85632676 | | | | | | |
| 7 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 8 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 9 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 10 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 11 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 12 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 13 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 14 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 15 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 16 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 17 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 18 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 19 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 20 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |

**A-3.** Excel snapshot of example 2, scenario 1

| Mill SL | TMX SL | | Mill LT (LTS) | TMX LT (LTD) | OI | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.9 | 0.95 | | 40 | 8 | 4 | | | | | | | | |
| Period | Demand Distributions | | | | | | | | | | | | |
| | Mean | Std Dev | SSD | SSS | | SST | Total Inv | | Mean | Std Dev | | SST | Total Inv |
| 1 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | 19,722.58 | 24,722.58 | | 100,000.00 | 2,213.59 | | 14,041.04 | 64,041.04 |
| 2 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 3 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | Gap | 39,318.46 | | | | | | |
| 4 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 5 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 6 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 7 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 8 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 9 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 10 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 11 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 12 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 13 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 14 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 15 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 16 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 17 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 18 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 19 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |
| 20 | 10,000.00 | 700.00 | 1,151.40 | 1,040.00 | | | | | | | | | |

**A-4.** Excel snapshot of example 2, scenario 2

| Days Late | Count | Prob | Cum Prob | | SS (in lbs) | | SST1 (in lbs) |
|---|---|---|---|---|---|---|---|
| 0 | 900 | 0.9 | 0.9 | | 0.00 | | 0.00 |
| 1 | 20 | 0.02 | 0.92 | | 200.00 | | 2000.00 |
| 2 | 15 | 0.015 | 0.935 | | 300.00 | | 3000.00 |
| 3 | 10 | 0.01 | 0.945 | | 300.00 | | 3000.00 |
| 4 | 6 | 0.006 | 0.951 | | 240.00 | | 2400.00 |
| 5 | 7 | 0.007 | 0.958 | | 0.00 | | 0.00 |
| 6 | 7 | 0.007 | 0.965 | | 0.00 | | 0.00 |
| 7 | 7 | 0.007 | 0.972 | | 0.00 | | 0.00 |
| 8 | 4 | 0.004 | 0.976 | | 0.00 | | 0.00 |
| 9 | 4 | 0.004 | 0.98 | | 0.00 | | 0.00 |
| 10 | 2 | 0.002 | 0.982 | | 0.00 | | 0.00 |
| 11 | 1 | 0.001 | 0.983 | | 0.00 | | 0.00 |
| 12 | 3 | 0.003 | 0.986 | | 0.00 | | 0.00 |
| 13 | 1 | 0.001 | 0.987 | | 0.00 | | 0.00 |
| 15 | 1 | 0.001 | 0.988 | | 0.00 | | 0.00 |
| 18 | 1 | 0.001 | 0.989 | | 0.00 | | 0.00 |
| 19 | 1 | 0.001 | 0.99 | | 0.00 | | 0.00 |
| 20 | 1 | 0.001 | 0.991 | | 0.00 | | 0.00 |
| 27 | 1 | 0.001 | 0.992 | | 0.00 | | 0.00 |
| 30 | 2 | 0.002 | 0.994 | | 0.00 | | 0.00 |
| 32 | 1 | 0.001 | 0.995 | | 0.00 | | 0.00 |
| 33 | 1 | 0.001 | 0.996 | | 0.00 | | 0.00 |
| 38 | 2 | 0.002 | 0.998 | | 0.00 | | 0.00 |
| 50 | 1 | 0.001 | 0.999 | | 0.00 | | 0.00 |
| 99 | 1 | 0.001 | 1 | | 0.00 | | 0.00 |
| Total | 1000 | 1 | 1 | | 1040.00 | | 10400.00 |

**A-5.** Excel snapshot of calculation of supply side safety stock for example 2

| | | | | |
|---|---|---|---|---|
| h | 0.2 | | | |
| C | 2 | | | |
| S | 5000 | | | |
| | | | | |
| | Mat | Ord | Hold | Total |
| TAC(S1) | 260,000.00 | 65,000.00 | 10,765.59 | 335,765.59 |
| TAC(S2) | 260,000.00 | 65,000.00 | 9,889.03 | 334,889.03 |
| TAC(S1Tradit | 260,000.00 | 6,500.00 | 25,616.42 | 292,116.42 |

**A-6.** Excel snapshot of total annual costs for previous examples

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| lbs purchased | C | | | | | | | | | |
| 0 - 10,000 | 2 | | Q0 | 57,008.77 | | | | | | |
| 10,000 - 20,000 | 1.97 | | Q1 | 57,441.21 | | | | | | |
| 20,000 - 30,000 | 1.95 | | Q2 | 57,735.03 | | | | | | |
| 30,000+ | 1.9 | | Q3 | 58,489.77 | | | | | | |
| | | | | | | | | | | |
| Q3 | 58,489.77 | | Mill LT (LTS) | TMX LT (LTD) | OI | OI (wks) | Risk | | | |
| Mill SL | 0.90 | | 40 | 4 | 5.85 | 23.40 | 14.85 | | | |
| TMX SL | 0.95 | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| Period | Mean | Std Dev | SSD | SSS | | SST | Total Inv | | | |
| 1 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | 30,679.57 | 59,924.45 | | | |
| 2 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 3 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | C | 1.9 | | h | 0.2 |
| 4 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | S | 5000 | | | |
| 5 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 6 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | Mat | Ord | Hold | TAC | |
| 7 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | 247,000.00 | 11,113.06 | 22,771.29 | 280,884.35 | |
| 8 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 9 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 10 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 11 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 12 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 13 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 14 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 15 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 16 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 17 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 18 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 19 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |
| 20 | 10,000.00 | 700.00 | 1,151.40 | 1040.00 | | | | | | |

**A-7.** Excel snapshot of calculation for optimal ordering quantity due to an all unit quantity discount and the corresponding total annual cost

| With Qty Discount | | | | |
|---|---|---|---|---|
| | Mat | Ord | Hold | Total |
| TAC(S1) | 260,000.00 | 65,000.00 | 10,765.59 | 335,765.59 |
| TAC(S1Tradit | 247,000.00 | 6,500.00 | 25,616.42 | 279,116.42 |

**A-8.** Excel snapshot of total annual costs with quantity discounts factored in for scenario 1

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