Using System Dynamics to Evaluate A Push-Pull Inventory Optimization Strategy For Multi-Tier, Multi-Channel Supply Chains

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Abstract

Multi-tier, multi-channel supply chains are now common in many industries including aviation. Such supply chains provide high-value aviation parts to the Government, and many of these supply chains have been plagued recently by shortages. These shortages arise from demand volatility as well as supply uncertainties. In many commercial supply chains, a push-pull strategy is used to develop responsiveness to uncertainties in demand and supply. An optimization model is developed for an aviation supply chain to strategically place WIP inventory at specific suppliers, thus creating a push-pull boundary in the manufacturing supply chain. The optimum solutions are shown to substantially improve supply chain response and supply availability with reduced working capital. A system dynamics model is used to evaluate the performance of the supply chain over time when the optimal safety stocks were in place. The results indicate a significant improvement in the recoverability of the supply chain when subjected to a sudden increase in demand.

This research was conducted at the University of Alabama in Huntsville.

1. Introduction

Demand planning is a harsh reality because of a simple and straightforward fact: *the forecast is always wrong* (Simchi-Levi, 2004; Nahmias, 1997). Demand forecasting is especially challenging for products such as defense related aviation spare parts with long production lead times, unknown future operating environments, and uncertain political developments. This fundamental forecasting and planning requirement has been a problem for the proper management of Government supply chains for half a century or longer (Macy, 1945). Inventory shortages and backorders frequently afflict Government supply, although excess inventory has caused unnecessary expenditure as well (Thorne, 1999). The Government has had a long-term need for a strategy that would improve its ability to meet unexpected demands while minimizing expenditure. Numerous studies have been performed and suggestions made for meeting these requirements, but to date these issues continue to cause significant impacts that hinder readiness improvements and supply availability within the Government supply chain (Abramson and Harris, 2003; Gansler and Luby, 2004; Folkeson and Brauner, 2005). This paper presents an approach for an innovative strategy for improving availability of aviation spare parts in an efficient and effective fashion.

Figure 1 presents an overview of the extended enterprise supply chain for aviation spare parts. This supply chain extends from raw material producers through multi-tier production supply chains to a prime contractor integrator and then on to inventory and aircraft in global regions. In Figure 1, ten components are each produced in a three tier supply chain and then assembled into the final spare part. A subset of the ten components is required for depot overhaul and another subset is required for commercial overhaul. (Parts in need of repair are shipped to overhaul

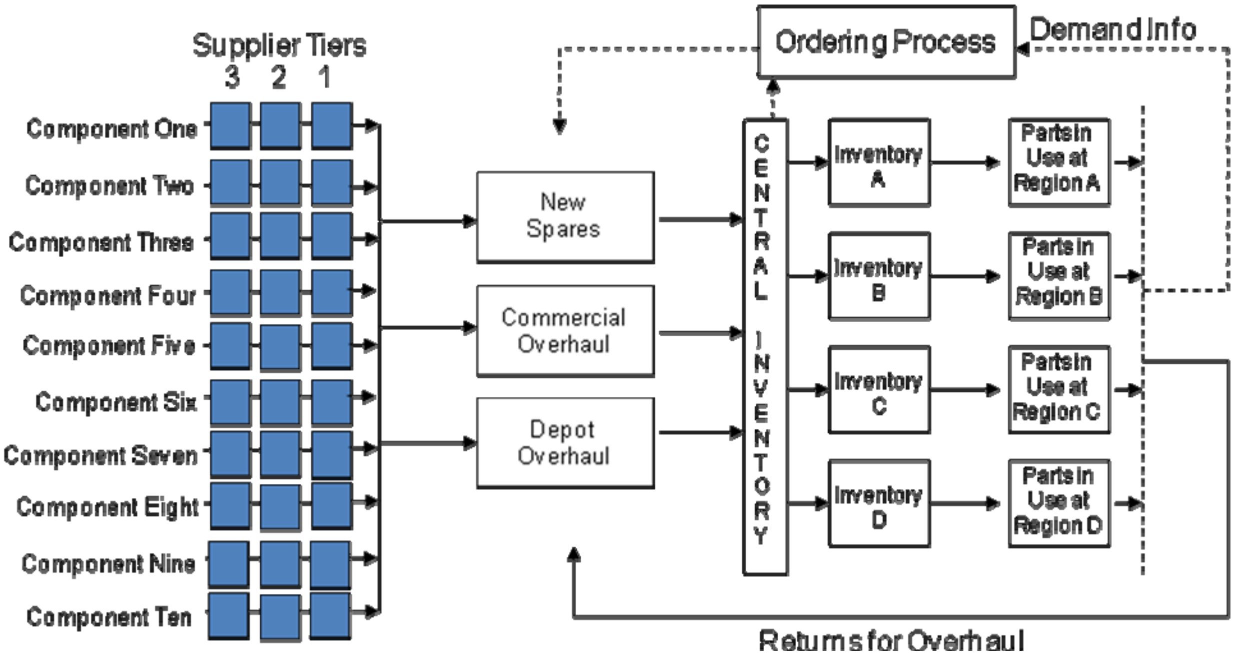


Figure 1: Overview of the Government Supply Chain for Aviation Parts

facilities after removal in the field.) New spares and overhauled spares enter a central inventory site and then are distributed to global inventory points based upon received orders. Regional demand is driven by the number of aircraft in each region, the monthly flight hours per aircraft in each region, and a failure rate per flight hour in each specific region. As may be seen in Figure 1, demand information flows back to the ordering process and is used to calculate future demands and future requirements. The ordering process through which demand information is used to calculate production and overhaul quantities is known as the requirements determination process and is based on algorithms that date back to the 1960's (Rosenman and Hoekstra, 1964). In this process, an averaging of historical demand (typically a twenty-four month rolling average) is used to predict future requirements, and this information, in addition to current due-ins and due-outs, is compared to available inventory levels to determine recommended buys and repairs. As orders for the new buys and repairs are processed and ultimately produced, available inventory is affected; thus, a feedback control system is apparent in which the feedback of demand information is central.

One approach that is often chosen to improve forecast accuracy is to apply more historical data to the forecasting calculations (Malehorn, 2001). Unfortunately, for many organizations, this historical data is not available, and when it is, the data is often inaccurate (Safavi, 2005). This is frequently the case for defense related items such as aviation spare parts. Furthermore, the current ordering process of the Government supply chain leaves very little room for data and/or forecast error. The principal method for calculating recommended buys and repairs is based upon determining the difference between two large numbers (Killingsworth, Chavez, and Martin, 2008). As a result, relatively minor standard deviations among the original terms compound to cause significant error in the resulting orders. This can have a highly negative effect on the efficacy of the entire demand planning and ordering process.

Rather than trying to improve the forecasting calculations, Rand Corporation suggests focusing on improving supply chain responsiveness (Folkeson and Brauner, 2005). One straightforward strategy for increased responsiveness is simply to hold a substantial amount of safety stock in a "push" supply approach. The safety stock inventory levels are pre-determined based on anticipated demands. In this tactic, spare parts are "pushed" out to global regional distribution centers awaiting orders from customers. This strategy is shown in Figure 2 as Line A. This approach, while improving responsiveness, can be extremely costly due to the high cost of holding large regional inventories of finished spare parts (Case Study, 2004). Curve A in Figure 3 illustrates the commonly held view between readiness (supply availability) and investment in stocks. As higher levels of readiness are targeted, a much higher level of investment in required. This is illustrated by the blue arrow in Figure 3. In other words, add money and move up the readiness curve.

Another approach is to introduce a push-pull strategy in the distribution portion of the extended supply chain. In such a strategy, parts with higher monthly demand and lower demand variability are pushed out to the regional inventories since the demand requirements are fairly well known. On the other hand, parts with low monthly demand and high demand variability tend to be held in the central inventory. This aggregates demand volatility across the regions and holds stock that can then be sent where needed, thus reducing costs. This approach is shown as Line B in Figure 2. Improvement in readiness is no longer achieved by moving from point to point on Line A; the optimization strategy creates a completely new relationship curve between readiness and investment. On line B, it requires a much smaller investment to achieve the targeted readiness. This is illustrated by the green arrow on Figure 3.

Yet another strategy is to create a “push-pull” boundary within the multi-tier, multi-channel manufacturing supply chain (Simchi-Levi, 2008). The location of the boundary depends on the committed service time (CST) of the final product and the variability of demand. In this circumstance, inventories of certain work in progress (WIP) items are created (pushed forward) in the manufacturing supply chain. These WIP inventories are then available to be used in the manufacturing process depending upon customer demand pull. For example, certain forgings or castings might be held in inventory to avoid long waits for raw materials and the casting or forging process. Importantly, these items have relatively low value added since much of the final value is added later through, for example, labor and capital intensive precision machining. This holding of lower value added items contributes to the cost savings of this approach.

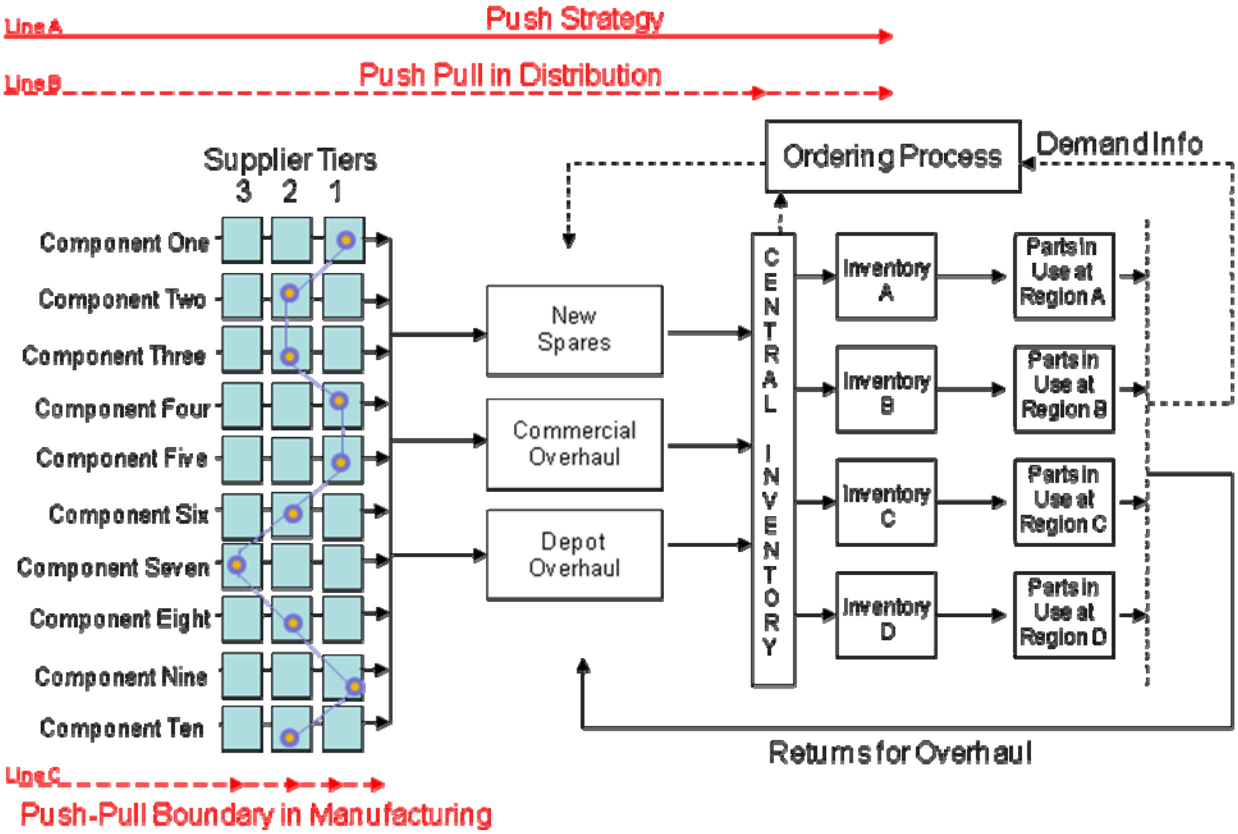


Figure 2: Push Strategy Compared to Push-Pull Strategy

Determining the appropriate inventory levels within the manufacturing supply chain requires conducting a trade-off analysis between the holding cost of the inventory, the value added along the tiers, the production time at each tier, average demand levels, variability of demand and required customer service time. In general, the shorter the required customer service time, the larger the inventory needed and the closer to the final product. If longer service times are acceptable, then inventories can be smaller and placed farther back in the supply chain, that is, in the lower tiers of the manufacturing supply chain. This analysis can be structured as an optimization problem solving for the lowest cost given required customer service time, demand levels, demand variability, manufacturing times and value added within the channels of the supply chain network. The solution determines the optimal level of WIP safety stock for each supplier in the supply chain, creating a boundary between the push and pull systems. This strategy creates yet another relationship between readiness and investment in which very little additional investment is required to achieve the targeted readiness. This is achieved by optimally holding lower value-added inventory to enable responsiveness.

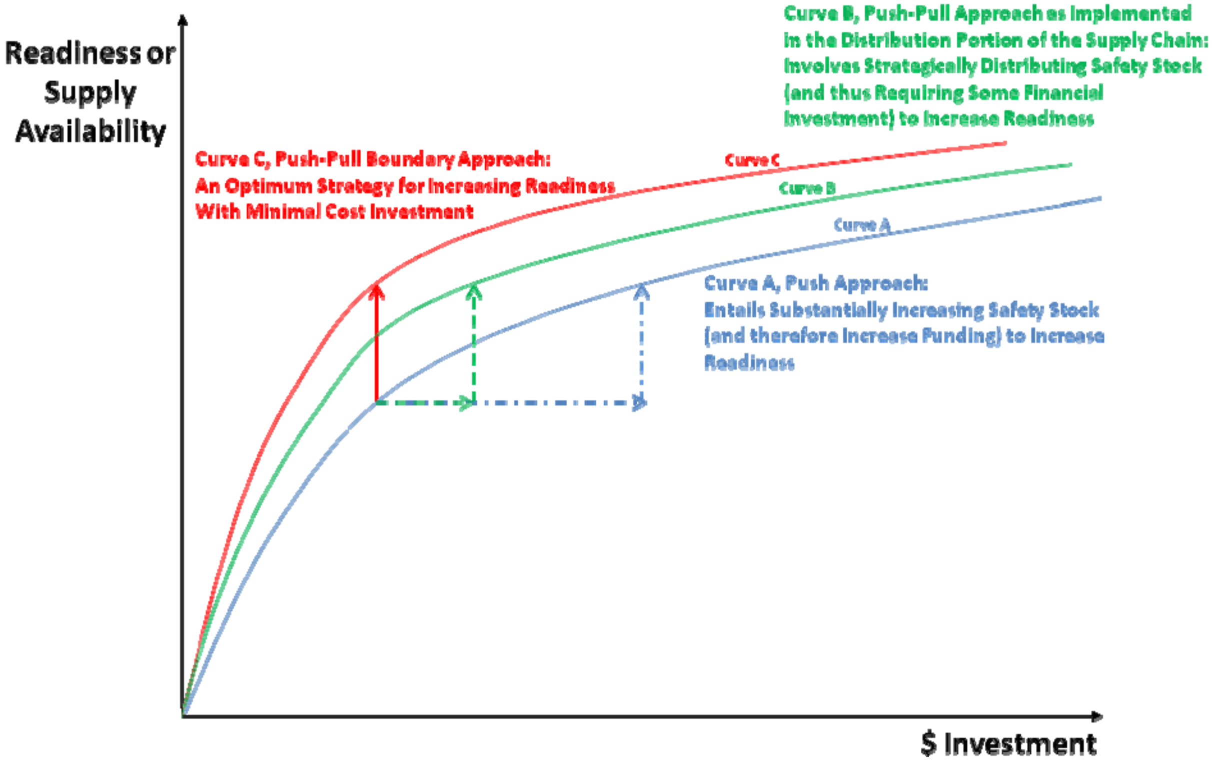


Figure 3: Supply Strategies Relative to Cost

2. Optimization Approach

The importance of using optimization software tools for inventory management in the Government sector was emphasized in a Jane's Defense Weekly article almost a decade ago (1999). Despite this early analysis, even recent GAO reports have indicated the need for continued analysis of safety stock levels (2007). Additionally, Rand Corporation has conducted research into Government supply chains and has noted that increased inventory management would benefit readiness capabilities (2005). Inventory management policies, including maintaining key amounts of safety stock throughout the supply chain, create a balance of push and pull supply chain strategies, an approach that according to David Simchi-Levi may be ideal (2008). Villa and Watanabe conducted a detailed analysis of this push-pull combination more than a decade ago (1993). More recently, a number of researchers have analyzed push-pull strategies and optimization techniques and their affect on commercial and Government supply chains. Minnich and Maier have thoroughly discussed the benefits and drawbacks of push and pull strategies (2007). Rand has suggested applying push-pull supply chain techniques to the Government supply chain (2005). Chandra and Grabis discuss inventory management and its affect on lead time and cost (2006). Lan et al. address optimization of order quantities and lead times (1999) and and Simchi-Levi and Zhao discuss safety stock optimization in supply chains with varying lead times (2005). Lee et al. apply optimization techniques to aircraft parts allocation (2008). Killingsworth, Chavez, and Martin conduct a thorough analysis of the Government supply chain through the application of high-value aviation spare parts in a multi-channel, multi-echelon system dynamics supply chain model that embeds the government ordering process (2008). The intent of the current research is to apply optimization techniques to the inventory management of the Government supply chain for a high value aviation part. The approach uses a commercial software package that establishes a balance of push and pull and thus helps to increase readiness, limit stock-outs, and shorten recoverability from increased changes in demand.

It must be noted that the optimization process is a steady state or static solution. That is, it determines optimum WIP inventory given a specific constant average demand level (mean demand) and constant demand variability (standard deviation of demand) and a committed customer service time. If a different average demand is assumed, then a different optimal solution is calculated as would be expected. It is important, therefore, to understand and evaluate likely supply chain performance given optimum WIP inventories but time varying demand scenarios such as a sharp surge in demand. To test and evaluate the optimum solutions, a dynamic simulation model has been developed of the extended multi-tier, multi-channel extended enterprise supply system illustrated in Figures 1 and 2. This model simulates the behavior and performance of the extended supply chain for alternative assumptions of WIP inventory and time varying demands. Optimum WIP inventories for example are established in the manufacturing supply chain and part availability over time is evaluated and measured via simulations with alternative demand scenarios.

3. Description of the Optimization Process

The software used for the current research is Inventory Analyst, a commercial inventory optimization software package developed and distributed by LogicTools, a division of ILOG. Inventory Analyst is widely used by major corporations for supply chain design and optimization. Users include such supply chain leaders as Colgate-Palmolive Company, ConAgra Foods, and Kraft.

Inventory Analyst requires as input a basic map of the supply chain being analyzed. Figure 4 shows the supply chain map for the part being analyzed in this pilot study, a helicopter main rotor blade that consists of ten key, long-lead time parts. This map shows the supply network for the production of the new helicopter blade. The overall supply chain is comprised of numerous suppliers that each ultimately produce a component that is then integrated into a final assembly process at the OEM. The diagram also includes the estimated production lead time (in days) of each of the manufacturing processes. Also indicated are the number of each component parts that is needed in the final assembly. The first nine components are considered critical items in that they have the longest lead times. They are therefore principal determinants of the lengthy delay in the ordering process for this aviation part. Component ten is a “catch-all” bin for the remaining items that comprise the final product.

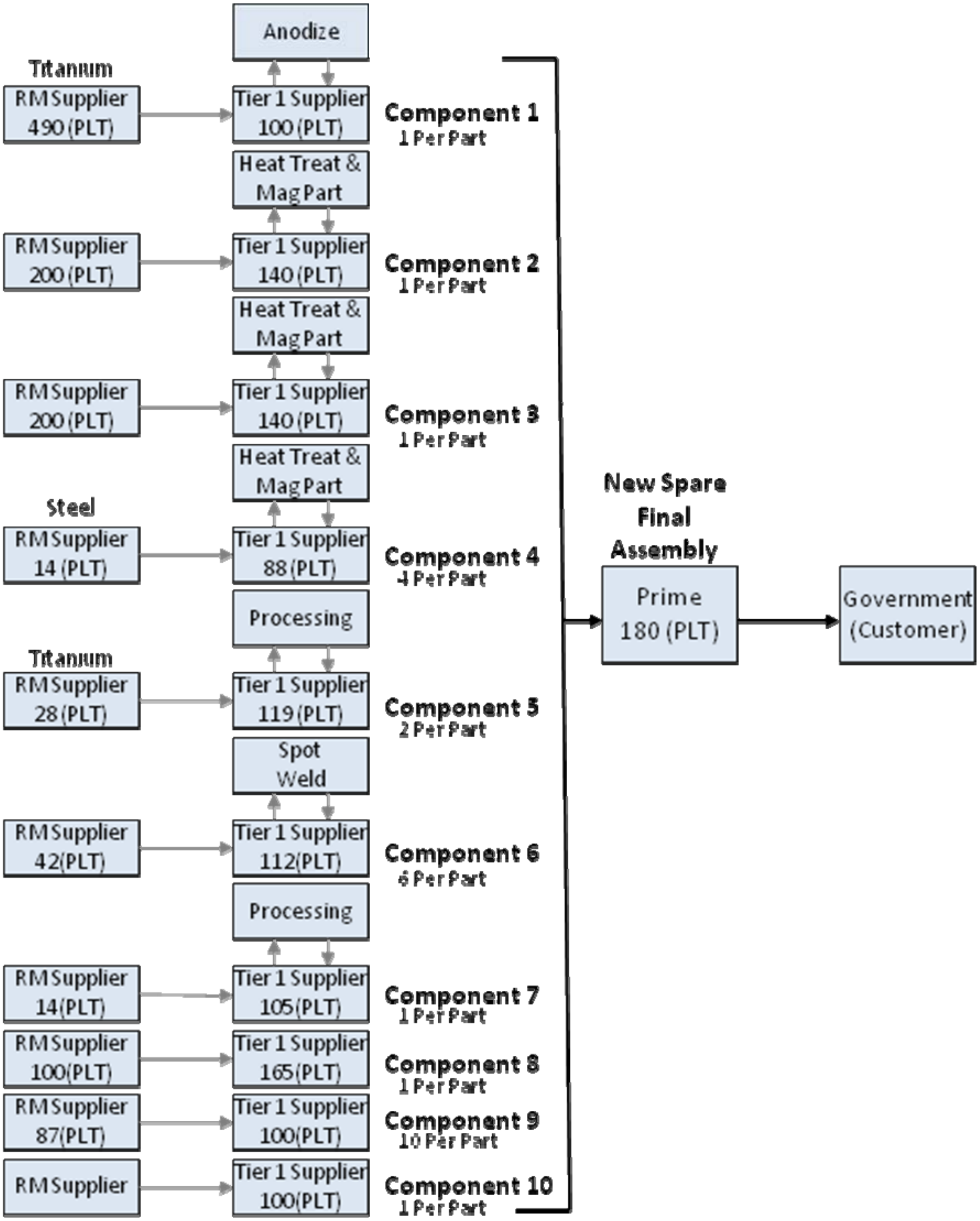


Figure 4: Overview of a Multi-Tiered, Multi-Channeled Aviation Supply Chain

Figure 5 presents a similar map for the necessary parts required for the overhaul of a blade.

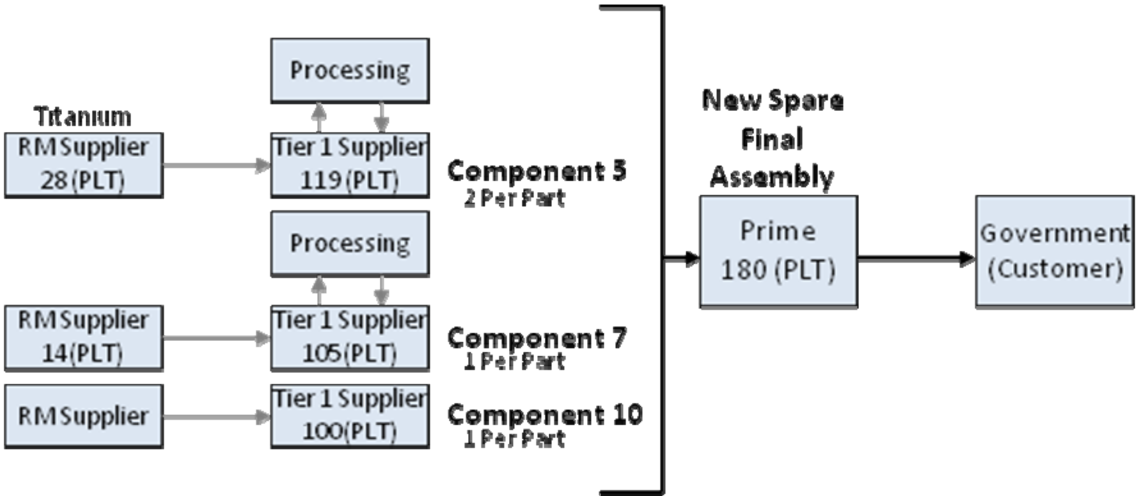


Figure 5: Overview of the Aviation Repair Process

Figure 6 shows an expanded and integrated view of the flows present in Figures 4 and 5 and in the model. For this particular part, all overhaul is conducted commercially; there is no depot overhaul. As seen in Figure 5, overhaul requires only three of the ten components, while new production requires all of the components to produce the final product. The map in Figure 6 shows the safety stock placement opportunities. For example, raw material may be held at the raw material supplier or at the Tier 1 supplier. Similarly, a component may be stored at its originating supplier or at the subsequent assembly location. Each of these possibilities is taken into consideration in the optimization process.

In the optimization model, demand originates in the Government sector, which is defined as a consumption based customer. Overall demand is assumed to be twenty-two blades per month. The loss and scrap rate for the blades in the field is assumed to be 6%, that is, only 94% of the removed blades are returned to be evaluated for overhaul. The scrap rate at the overhaul facility is assumed to be 46%. Thus for twenty-two blades being removed each month, 11 end up being available for overhaul (22*(1-0.06)*(1-0.46)). The remaining demand must therefore be met with production of new blades. There is thus, in summary, a monthly demand for eleven new blades and eleven overhauled blades. Each of the necessary components is then ordered depending upon the number needed for each new part and each overhauled part. Some components are needed in higher quantities to create a final product, while only one of other components is needed to complete a part. Figure 4 provides details on the required number of components per part. Each component furthermore has a separate lead time for each step of the supply chain process. Therefore the total lead time for the component with the longest lead time plus the final assembly time at the OEM is the overall total production lead time for the final product. It is important to note that the production lead time (PLT) for the OEM is 180 days. Thus, it takes six months to assemble the final product after all of the components have been received. This production time is very long and is a major factor in the optimization for required inventories and associated costs. Impacts of reducing this PLT are studied in the optimization calculations. The Repair Lead Time (RLT) is similarly a very lengthy process at the OEM. The repair process requires the replacement of designated components (two of which in this case are considered critical items) and completion of the final assembly. The impacts of reducing this RLT are also studied in the optimization calculations.

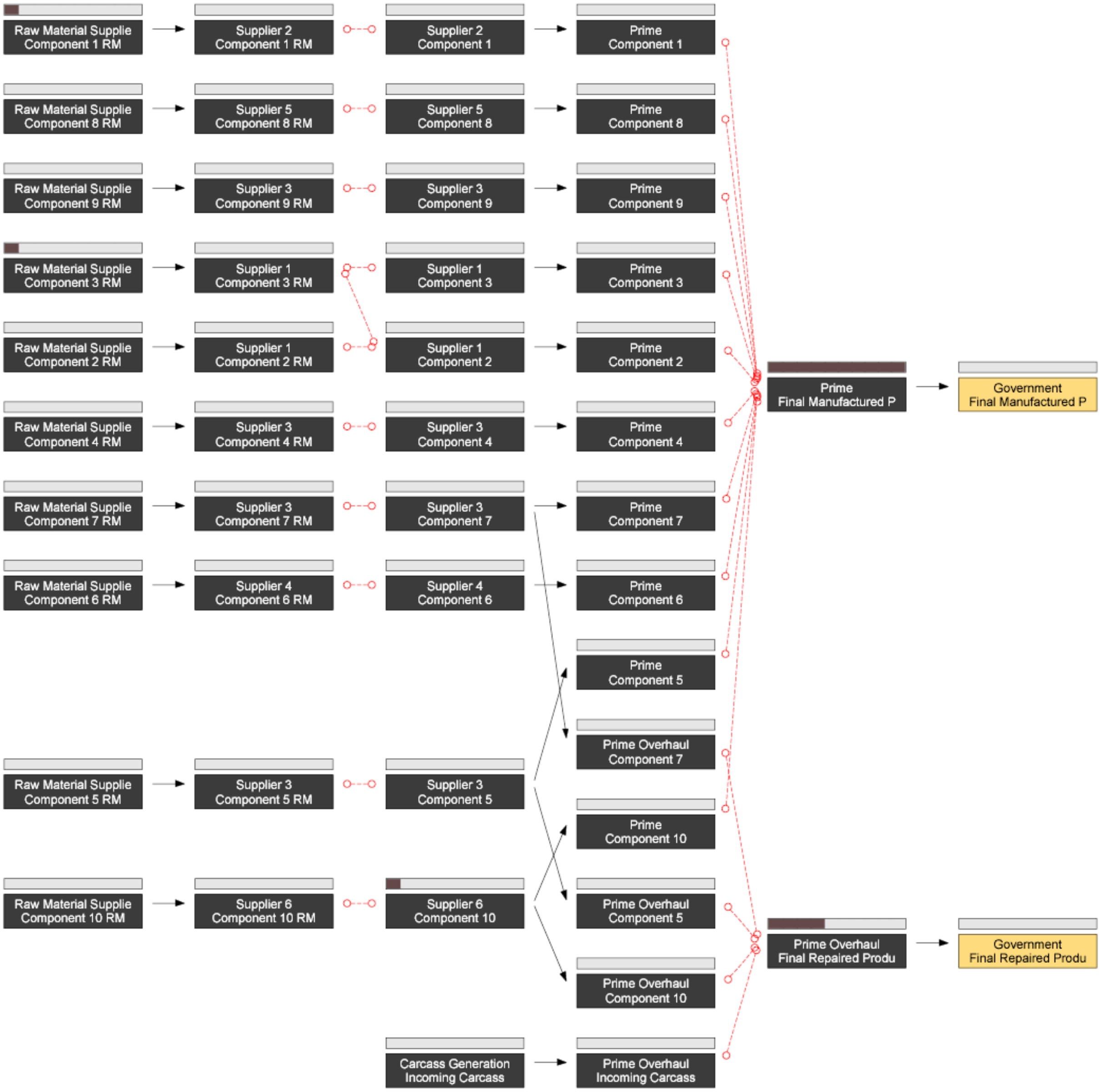


Figure 6: Detailed Layout of the Optimization Inventory Analyst Model

The optimization model also incorporates the cost of each component as well as the cost of the final product. In this case, the overall cost of the final product is assumed to be $175,000. The OEM pays a total of 50% of that cost for the parts needed to assemble the final product, broken down such that Component 10 comprises 20% of the OEM's cost, Components 1 and 4 each comprise 15% of the OEM's cost, Components 2, 3, and 8 each comprise 10% of the OEM's cost, and Components 5, 6, 7, and 9 each comprise 5% of the OEM's cost. First tier suppliers then pay 50% of the OEM's cost for the parts needed to assemble their products. This assumptions approximate proprietary costing data. The holding cost of each component is assumed to be 20% of its value. The model uses these key input assumptions to determine an optimum safety stock level based on specified assumptions in committed service time, demand level, forecast error (demand variability), and production lead time at the OEM.

4. Inventory Analyst Cases and Results

Inventory Analyst (IA) optimizes stocking levels within a supply chain to achieve lowest cost in the presence of demand uncertainty and a committed service time. The optimized solution provides the optimum safety stocking level at each location where stocking is allowed. This solution is based upon specific assumptions for parameters such as Committed Service Time (CST), the response time from the order point of a product to the delivery point; Fill Rate, the percentage of orders that are filled on time; Production Lead Time (PLT), the time it takes to manufacture a product; Repair Lead Time (RLT), the time it takes to replace designated components and complete the final assembly process; and Work in Progress (WIP), inventory that is still in a production stage prior to being available to meet demand.

In all of the cases considered below, average total monthly demand is assumed to be twenty two, with demand for eleven new spares and eleven overhaul spares as noted earlier. For each major category of case, optimum solutions are presented with Committed Service Times (CST) of 30, 90, and 240 days:

Case 1: OEM's PLT is 180 days and RLT is 90 days, and no safety stock is created in the manufacturing tiers (this more or less represents the current situation);
Case 2: OEM's PLT is 180 days and RLT is 90 days, and safety stock in the manufacturing chain is optimized;
Case 3: OEM's PLT is 120 days and RLT is 60 days, and no safety stock is created in the manufacturing tiers;
Case 4: OEM's PLT is 120 days and RLT is 60 days, and safety stock is optimized in the manufacturing chain;

4.1 Production Lead Time of 180 Days and 90 Days

Table 1 and 2 present the Inventory Analyst solutions when OEM PLT is 180 days for new products and 90 days for overhaul products. Table 1 provides the optimum solutions when the IA model assumptions are structured to allow no safety stock in the manufacturing tiers. This assumption means that all parts below the OEM level are made to order, and the full production lead time for all components is felt by the OEM. This corresponds to the current situation in which there is little to no safety stock inventory in the manufacturing supply chain. The cases in Table 1 thus solve for the safety stock that must be held by the OEM to maintain the fill rate and committed service time. Table 2 presents the optimum solution in which the IA model assumptions allow for the optimization of safety stock in the manufacturing tiers. Here, suppliers in the manufacturing tiers hold safety stock of components and component raw materials to maintain fill rate to the government under the specific assumptions.

In all cases a 95% fill rate is assumed, i.e., 95% of all orders are filled within the Committed Service Time. The first column of each table gives the demand uncertainty (as a standard deviation) assuming a mean demand of 11 per month for both the new and overhaul products. The tables present the solutions for three different levels of demand uncertainty; the demands for each type of product (new and overhaul) are 11 ± 3, 11 ± 6, and 11 ± 9. The second column presents the four levels of assumed CST. The tables then present the associated working capital tied up in inventory, the safety stock levels for new spares and overhaul spares. Finally, inventories are also presented for finished Component 1 and raw materials for Component 1. These inventories are presented because Component 1 is the component with the longest production lead time and thus illustrates the nature of the optimum solutions.

It is important to note that in these cases, Inventory Analyst has been configured to use the Skellam distribution that has the assumed standard deviation, but no non-zero probability, rather than a standard normal distribution. This selection of an IA capability eliminates the difficulties that may arise from that negative demand associated with a normal distribution. This is important for cases such as these in which the standard deviation is large relative to the mean.

As may be seen in Table 1, the calculated safety stock is zero for both Component 1 and the Raw Material for Component 1. This is because the IA optimization problem has been structured to disallow the storage of any safety stock in the manufacturing tiers. This forces all safety stock, necessary to maintain fill rate in the face of demand uncertainty, to reside in (expensive) finished parts at the OEM plant. As the CST decreases, the necessary safety stock of finished products increases, thus increasing working capital substantially. For example, a demand uncertainty of 3 requires a new spares safety stock of 3.1, making Working Capital approximately $24 million. On the other hand, a demand uncertainty of 9 combined with a CST of 30 requires 102 new spares in safety stock, making Working Capital over $49 million. Also note that Table 1 includes the case in which the CST is 770 days. This timeframe is approximately equivalent to the time required to produce an end item starting from its raw material. Very little safety stock is held and as a result the delivery time from order placement to order fulfillment is reprehensibly long. This situation exemplifies the current inventory policy and provides a basis for the long lead times typical in the aviation industry.

Table 1: Solutions with *no* stocking in the manufacturing tiers. All times are in days. OEM PLT is 180 days for new products and 90 days for overhaul products.

Demand Uncertainty	CST (days)	Working Capital ($)	New Spares Safety Stock	Overhaul Safety Stock	Safety Stock of Finished Component 1	Safety Stock of Component 1 Raw Material
3	30	31,075,380	29.7	16.6	0	0
	90	30,543,770	28.5	14.3	0	0
	240	27,729,530	23.9	0	0	0
	770	24,075,310	3.1	0	0	0
6	30	40,028,020	64.7	36.6	0	0
	90	38,760,630	62.5	30.3	0	0
	240	33,003,230	53.9	0	0	0
	770	24,778,470	7.1	0	0	0
9	30	49,192,260	102	55.6	0	0
	90	46,977,490	96.5	46.3	0	0
	240	38,276,930	83.9	0	0	0
	770	25,481,630	11.1	0	0	0

In Table 2, the manufacturing safety stock is no longer zero; Inventory Analyst optimizes the safety stock levels at all locations. Notice the substantial reduction in working capital as compared to Table 1, particularly for the high demand uncertainty cases. Note that in Table 1, for the 30 day CST with demand uncertainty 9, 102 new products must be stored at the OEM if no safety stock is allowed in the manufacturing tiers, but, as seen in Table 2, only 41.1 are recommended if manufacturing safety stock is allowed. The much less expensive manufacturing safety stock is sufficient to maintain fill rate at a much lower level of working capital.

Table 2: Solutions with stocking in the manufacturing tiers. All times are in days. OEM PLT is 180 days for new products and 90 days for overhaul products.

Demand Uncertainty	CST (days)	Working Capital ($)	New Spares Safety Stock	Overhaul Safety Stock	Safety Stock of Finished Component 1	Safety Stock of Component 1 Raw Material
3	30	29,091,250	11.1	8.5	11.1	24.4
	90	27,173,290	8.8	0.6	11.1	24.4
	240	25,285,860	0.8	0.0	7.5	24.4
6	30	34,577,050	26.8	18.5	22.6	52.4
	90	31,154,050	19.8	1.6	23.1	52.4
	240	26,452,480	0.90	0	16.3	52.4
9	30	40,512,690	41.1	28.5	37.1	81.4
	90	35,271,080	30.8	3.5	36.1	81.4
	240	27,766,950	1.0	0	25.4	81.4

Figure 7 corresponds to the solution in Table 2 for a demand uncertainty of 3 and a CST of 240 days. The expanded section shows the recommended safety stock placement in the Component 1 supply chain. Essentially, 24 units of raw material and 7 units of completed Component 1 product should be stored at the Tier 1 supplier. These stock levels reduce CST without the sacrifice of an extensive budget, as noted in the graph in Figure 8.

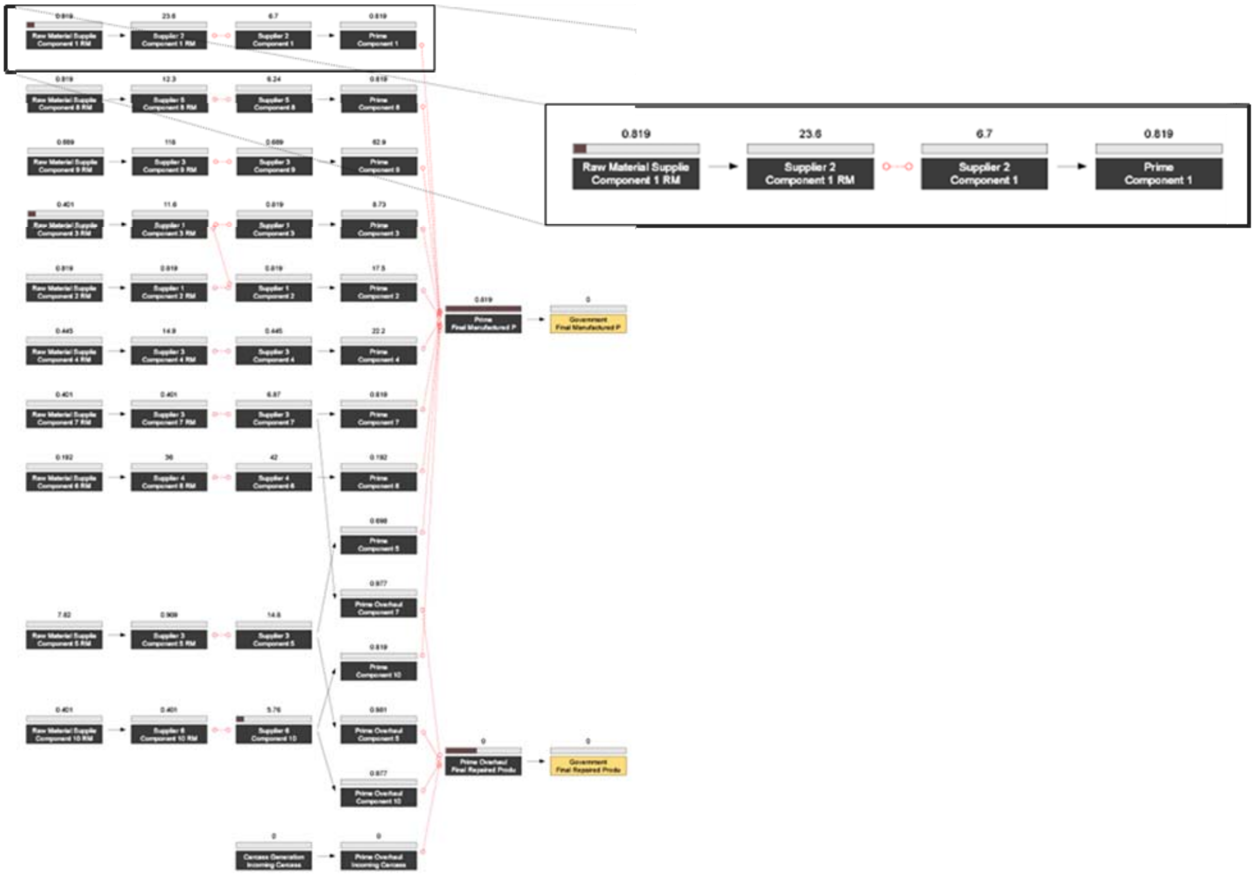


Figure 7: Optimization Results for a 240 Day CST and Demand Uncertainty of 3; OEM PLT is 180 Days for New Products and 90 Days for Overhaul Products

Figure 8 presents a graph of the working capital as a function of CST for the three demand uncertainties of 3, 6 and 9 as presented in Table 1 and Table 2. The red line is the case of no stocking in the manufacturing tiers, and the green line is for the case with stocking in the manufacturing tiers. Note the substantial reductions in cost for low CSTs. Also note that while cost is essentially linear upward from 770 days for the no stock case, it is nearly flat for the stocking case down to a CST of about 200 days. Given that the current orders take 770 days to be filled, one can immediately cut the CST by nearly a factor of four with virtually no increase in cost, *if* stocking is allowed in the manufacturing tiers.

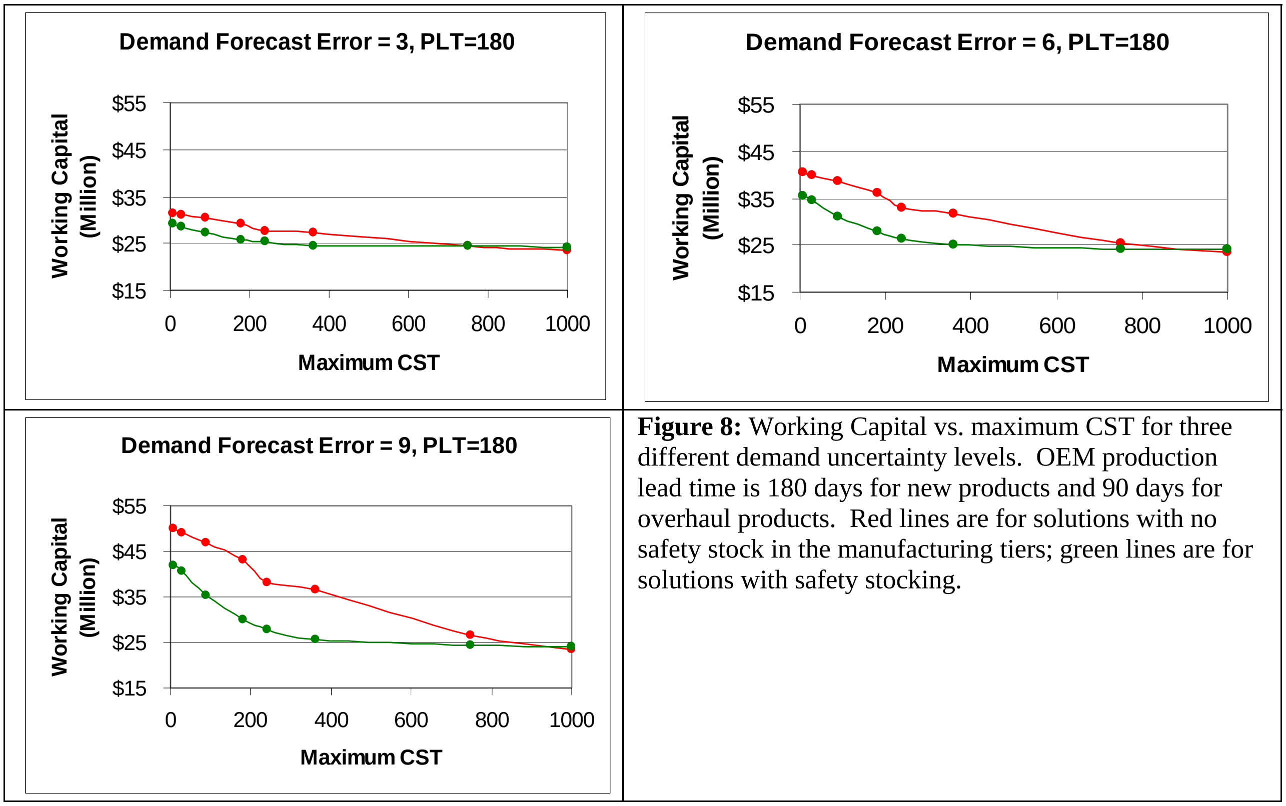


Figure 8: Working Capital vs. maximum CST for three different demand uncertainty levels. OEM production lead time is 180 days for new products and 90 days for overhaul products. Red lines are for solutions with no safety stock in the manufacturing tiers; green lines are for solutions with safety stocking.

4.2 Reduced OEM Production Lead Time of 120 Days and 60 Days

An additional strategy for improving availability and reducing working capital is to reduce the production lead time (PLT) at the OEM, by, for instance, adopting lean techniques and practices. Table 3 and Table 4 are identical to Table 1 and Table 2, respectively, except that Table 3 and Table 4 are for the OEM PLT of 120 days for new products and 60 days for overhaul products, rather than 180 days and 90 days, respectively. Not surprisingly, the Working Capital goes down substantially compared to the cases presented in Tables 1 and 2 with the same CST values. Much of this capital reduction, namely about $5 million arises purely from the reduced holding cost at the final assembly plant due to the lower PLT there. However, additional cost savings are realized because the safety stock levels necessary to accommodate demand uncertainty are much lower when the OEM can respond with greater agility. The greatest additional savings are realized for demand uncertainty of 9 and a 30 day CST with stocking in the manufacturing tiers allowed. Here, the additional benefit, as compared to the corresponding case presented in Table 2, is about $3 million. Comparison of the component safety stock levels in Table 4 with these entries in Table 2, we find little change in the safety stock levels until CST of 240, because the lead times are so long (100 days at Tier 1, and 490 days at Tier 2); however, for the OEM, safety stock levels drop dramatically.

Table 3: Solutions with *no* stocking in the manufacturing tiers. All times are in days. OEM PLT is 120 days for new products and 60 days for overhaul products.

Demand Uncertainty	CST (days)	Working Capital ($)	New Safety Stock	Overhaul Safety Stock	Safety Stock of Finished Component 1	Safety Stock of Component 1 Raw Material
3	30	25,352,210	28.5	15.4	0	0
	90	24,504,810	26.3	12.2	0	0
	240	22,163,160	22.7	0	0	0
6	30	33,849,060	62.5	33.4	0	0
	90	32,265,880	59.3	26.2	0	0
	240	27,085,280	50.7	0	0	0
9	30	42,345,920	96.5	51.4	0	0
	90	40,026,950	92.3	40.2	0	0
	240	32,007,400	78.7	0	0	0

Table 4: Solutions with stocking in the manufacturing tiers. All times are in days. OEM PLT is 120 days for new products and 60 days for overhaul products.

Demand Uncertainty	CST (days)	Working Capital ($)	New Safety Stock	Overhaul Safety Stock	Safety Stock of Finished Component 1	Safety Stock of Component 1 Raw Material
3	30	22,498,140	8.8	5.4	11.1	24.4
	90	21,092,450	4.6	1.0	11.1	24.4
	240	19,440,370	0.8	0	2.3	24.4
6	30	27,261,310	19.8	12.4	23.1	52.4
	90	23,951,860	10.6	1.0	23.1	52.4
	240	20,180,590	1.0	0	5.2	52.4
9	30	32,116,350	31.2	19.4	35.8	81.4
	90	27,053,680	17.6	1.0	36.1	81.4
	240	20,912,560	1.0	0	6.2	81.4

Figure 9 illustrates the necessary safety stock levels for the case in which the demand uncertainty is 3 and the CST is 240 days. The optimal safety stock level for Component 1 is 24 raw material units at the Tier 1 supplier, similar to the case in which the OEM's PLT was 180 days, but, in this case, only 2 completed components need to be stored at this supplier. This difference adds to the Working Capital savings that is illustrated in Figure 10, as compared to the longer PLT cases.

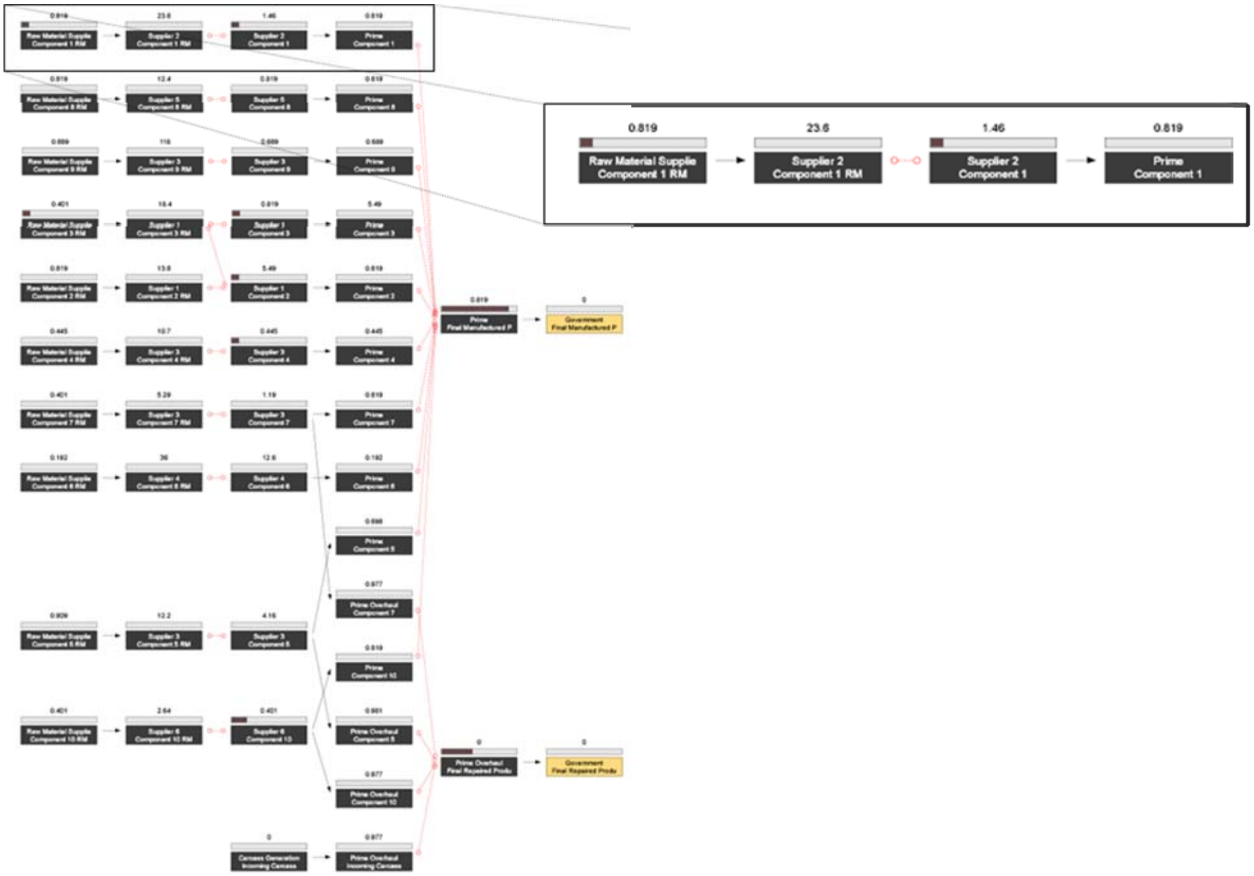
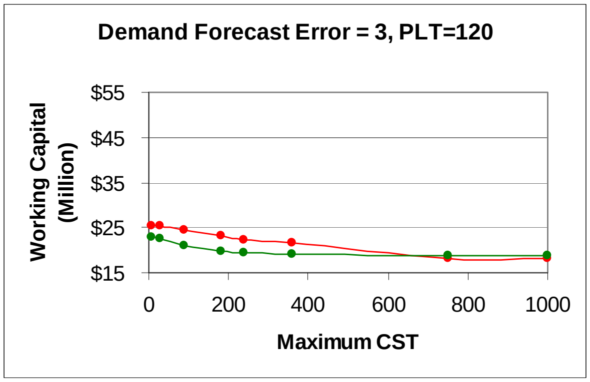
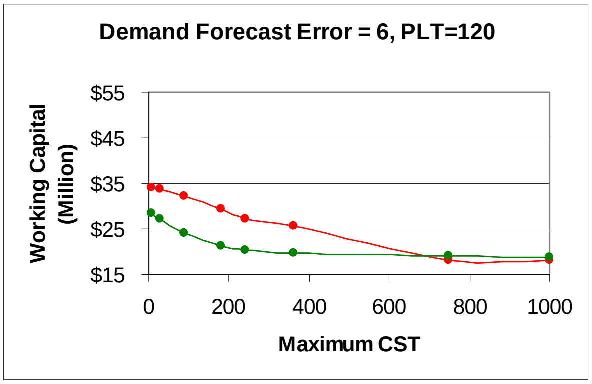


Figure 9: Optimization Results for a 240 Day CST and Demand Uncertainty of 3; OEM PLT is 120 Days for New Products and 60 Days for Overhaul Products

Figure 10 shows the working capital as a function of CST for the three demand uncertainties, 3, 6 and 9. These charts look qualitatively very similar to those in Figure 8. Again, the dominant difference is the fixed savings of about $5 million arising purely from reduced holding cost in final assembly. The subtler effect of the savings in safety stock is harder to observe qualitatively, although, from studying the tables, it can be seen that best additional gain is for a CST of 30 and demand uncertainty of 9; thus, a small change can be noted in the slope at that locus when comparing to Figure 8.





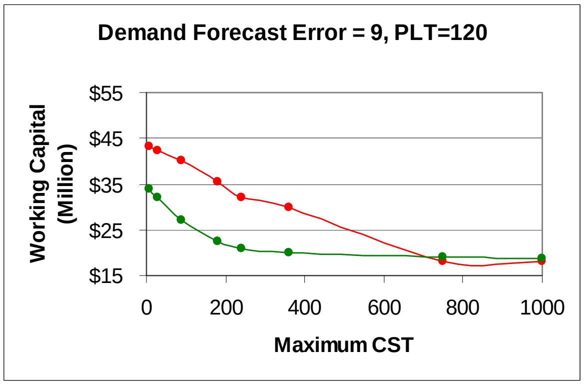


Figure 10: As in Figure 8, but for OEM production lead times of 120 days for new products and 60 days for overhaul products.

5. Simulation and Evaluation of Optimum Strategies

A system dynamics model of the Government supply chain was developed to simulate the performance of the extended supply chain in the event of a sudden increase in demand, an occurrence that has been common among aviation parts over the past five years. Killingsworth, Chavez, and Martin provide a detailed description of the system dynamics model built to simulate the Government ordering process (2008). An overview of the model is presented in Figure 11. The requirements determination algorithms are included in the Supply Chain Control Center, through which buys and repairs are recommended. These recommendations are based on separate calculations embedded in individual feedback control loops in the model.

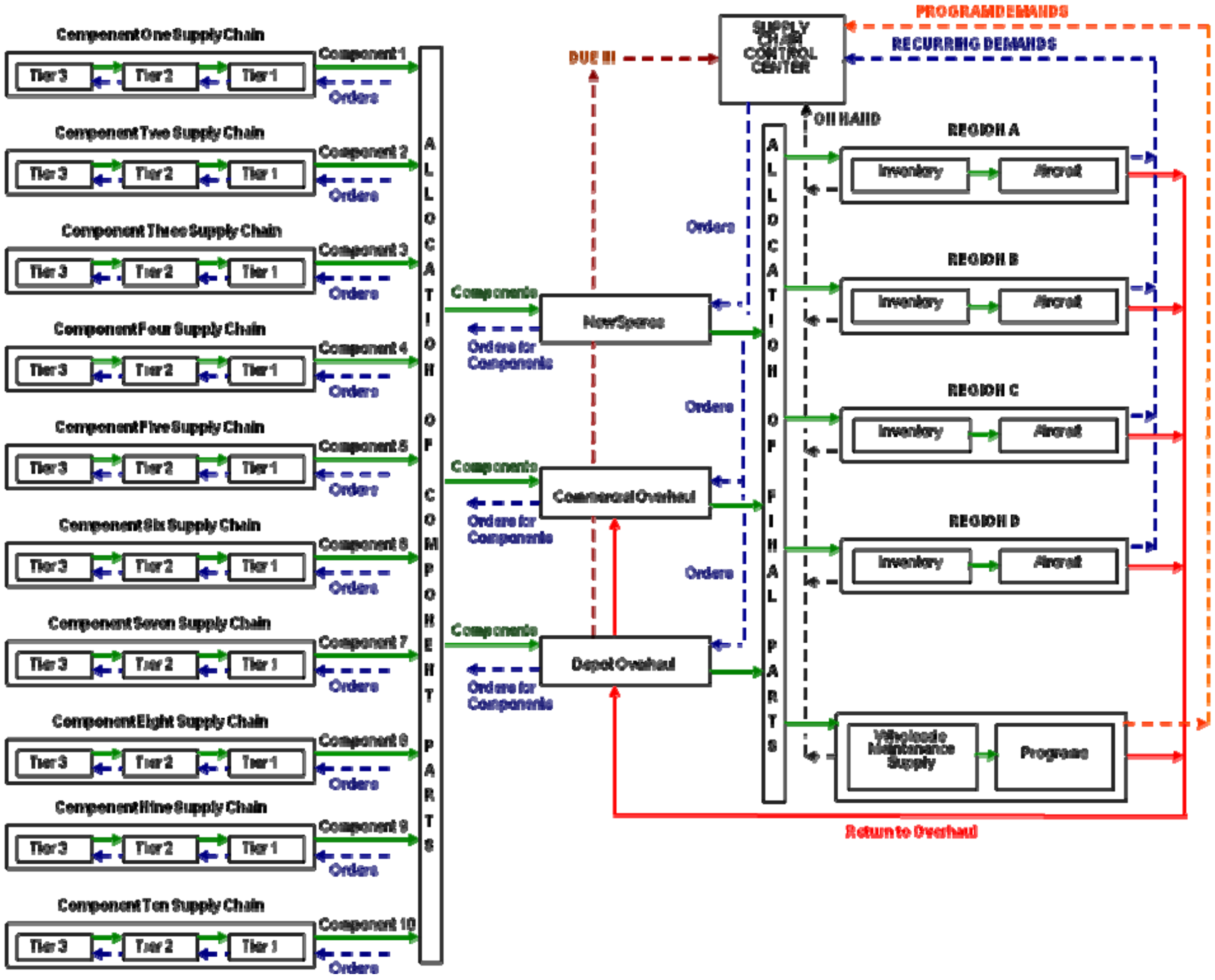


Figure 11: Overview of the Multi-Tiered, Multi-Channeled System Dynamics Supply Chain Model

Figure 12 presents the structure in the system dynamics model for the procurement process. The Total Net Assets are compared to the Procurement Reorder Point to determine whether a buy is recommended. If the Total Net Assets are less than the Procurement Reorder Point, the recommended buy is the difference between the two quantities plus the Procurement Cycle Requirement, which is the amount of inventory needed to meet the forecasted demands until the next scheduled order. Once the manufacturing process is complete, the new products are added to the due ins and calculated as part of the Total Net Assets.

The Recommended Repair Action is calculated similarly. The Assets Applicable for Repair Review is compared to the Repair Action Point. If the assets are less than the Repair Action Point, a maximum repair quantity is generated. In this case, however, the maximum repair quantity is compared to the available repairable carcasses to determine the Recommended Repair Action. When the repairs are complete, the refurbished parts are added to the available inventory and calculated into the Assets Applicable for Repair Review.

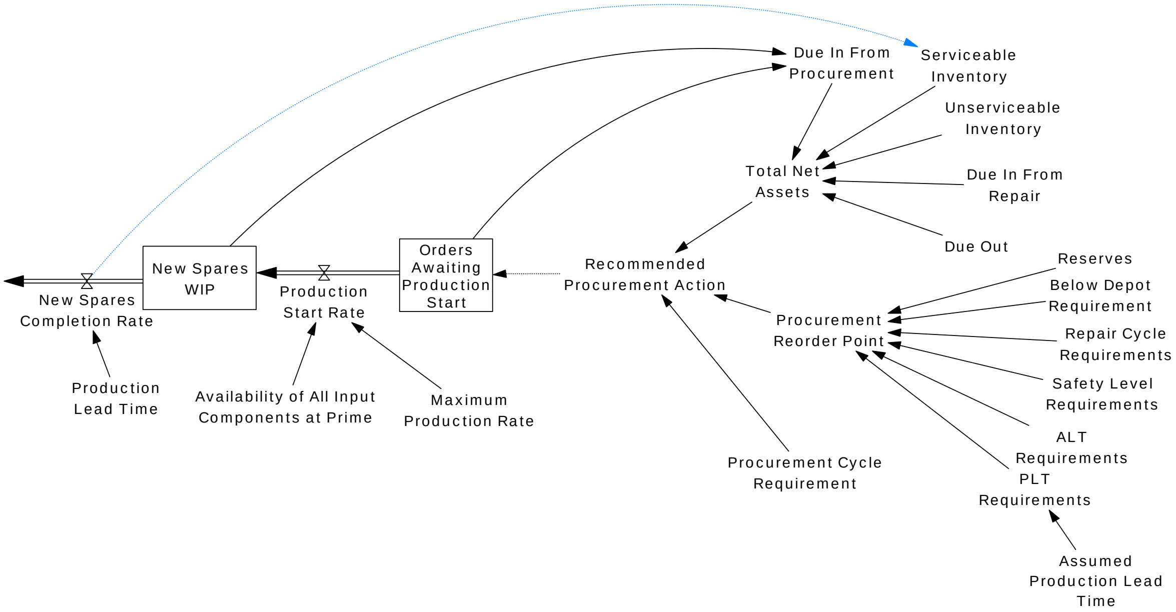


Figure 12: Recommended Procurement Action in System Dynamics Model

Once the procurement and repair orders are placed through the OEM, the process for procuring the necessary components for each action is initiated, and orders are placed through independent suppliers. The flow for one of the components is depicted in Figure 13. Due to the risks involved, suppliers generally do not hold safety stock; thus, when an order is placed, substantial lead times affect the ability of each supplier to immediately respond. After the orders have flowed through each of the tiers and products have been shipped back through each of the sub-assemblies, the OEM completes the final assembly process. The final product is then shipped to the central inventory site before being distributed to one of the regional inventories. Each of the final parts is then pulled for use on an aircraft. Any damaged parts, less a percentage that are considered loss or scrap, are returned to the overhaul sites to begin the repair process.

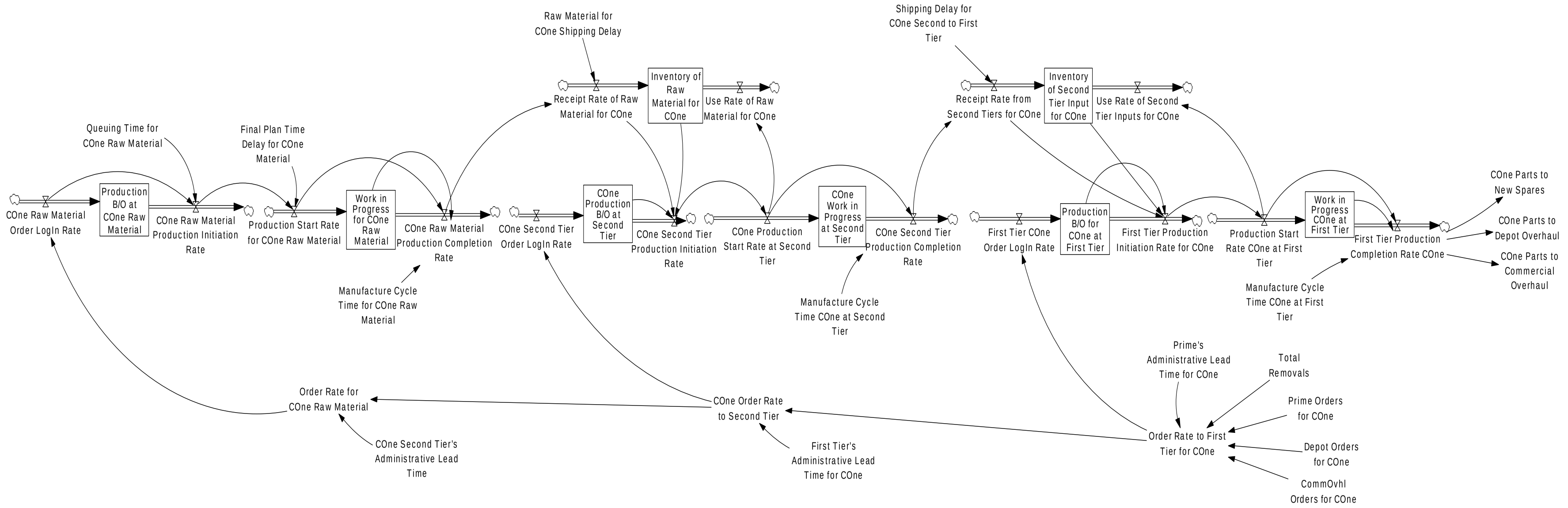


Figure 13: Supply Chain Tiers for Component One System Dynamics Model

5.1 Analysis and Simulation Results

A lack of safety stock combined with the lengthy lead times cause the responsiveness of the government supply chain to suffer. Therefore, key objectives of the analysis were to: (i) identify the current role of demand forecasting in supply planning; (ii) develop a strategy for risk mitigation; (iii) determine the recoverability of the government's requirements determination process if safety stock were strategically placed throughout the supply chain; and (iv) evaluate the impacts of implementing push-pull supply chain techniques into the Government supply chain. The system dynamics model has been parameterized for the same helicopter blade used in the Inventory Analyst cases. The dynamic model was then used to test the performance of the optimal solutions under alternative cases.

5.2 Simulation Cases

The optimization results presented in Tables 1-4 were evaluated for the 2001-2013 timeframe using the system dynamics simulation model to explore the recovery rate of inventory levels when a sharp increase in demand occurs at the beginning of 2003. The following cases are presented:

Case 1: OEM's PLT is 180 days and RLT is 90 days, the CST is 700 days, and no safety stock in the manufacturing tiers exists;
Case 2: OEM's PLT is 180 days and RLT is 90 days, the CST is 240 days, and safety stock is optimized;
Case 3: OEM's PLT is 180 days and RLT is 90 days, the CST is 30 days and safety stock is optimized;
Case 4: OEM's PLT is 120 days and RLT is 60 days, the CST is 700 days and no safety stock in the manufacturing tiers exists;
Case 5: OEM's PLT is 120 days and RLT is 60 days, the CST is 240 days and safety stock is optimized; and
Case 6: OEM's PLT is 120 days and RLT is 60 days, the CST is 30 days and safety stock is optimized.

Additional key assumptions for these cases include the following:

- Each component has a production lead time between 6 and 16 months;
- Overall PLT is 22 months and Overall RLT is 11 months;
- Demand begins at 14 units per month and increases to 20 units per month in 2003;
- All overhaul is conducted commercially with a maximum overhaul capacity of 15 units per month;
- New spare production is limited to 11 units per month;
- Unserviceable recovery rate is 94%, i.e., for every 100 parts issued, 94 are returned to the overhaul site; and
- Final recovery rate is 54%, i.e., for every 100 parts returned, 54 can be repaired and reissued.

The first case is the base scenario that represents the typical current conditions in which the OEM as well as the other suppliers throughout the supply chain carry no safety stock. Figure 14 shows the impact this limitation has on inventory levels when demand suddenly increases in 2003. Serviceable inventory is depleted for five years; thus, no issuable inventory is available on-hand at the central inventory site during that time. Inventory at each of the regions is also exhausted for over two years, and the supply system struggles to meet the new demand level. Stability does not return to the supply chain until well after the year 2013. The impact of this situation in the real world is profound when considered in context with war-time conditions such that lack of inventory means the completion of missions and ultimately human lives are at stake (Thorne, 1999).

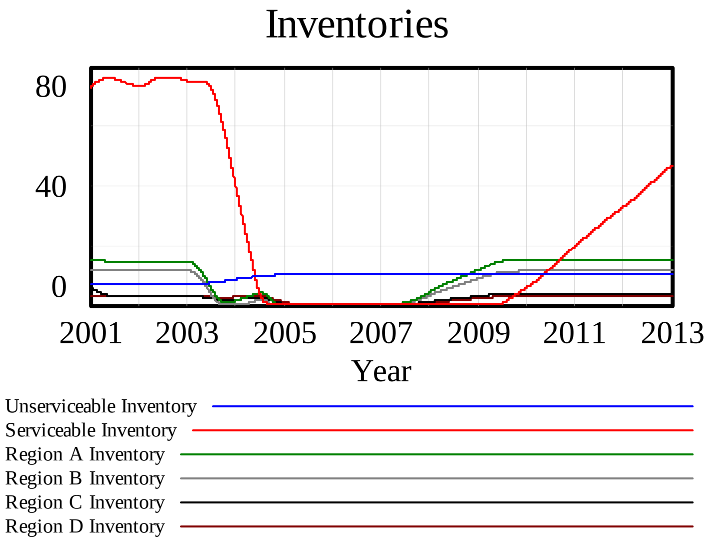


Figure 14: Case 1 Inventory Levels with an Increase in Demand in 2003; No Stocking in the Manufacturing Tiers Exists

Placing even limited inventory in a few strategic places, primarily at the Tier 1 suppliers, produces significant improvements from the base case. Consider implementing placement of inventory levels corresponding to the quantities displayed in the optimization results in Figure 7. Not only does the CST drastically improve from approximately two years to under a year, but the response rate of the supply chain also improves dramatically. In this case, as depicted in Figure 15, Serviceable inventory begins to recover in approximately three and a half years rather than five, and regional inventory recovers in approximately half the time as the base case (Case 1). As discussed previously, this change can be accomplished with relatively little change in Working Capital. Thus, even a minor investment can make a difference in the capabilities of the Government supply chain.

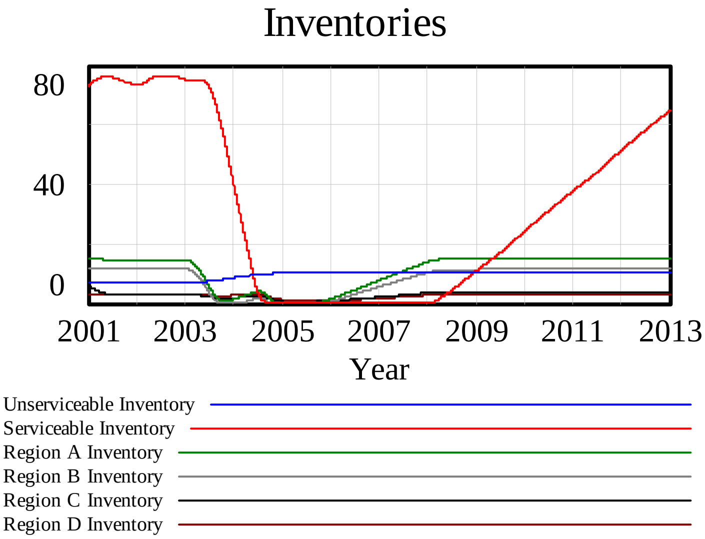


Figure 15: Case 2 Inventory Levels with an Increase in Demand in 2003; Stocking is Optimized and the CST is 240 Days

Additional improvements can be made with a larger investment in Working Capital, as displayed in Table 2. Increasing this investment through strategic placement of additional safety stock at the OEM and the Tier 1 suppliers further enhances the readiness of the supply chain. For example, placing inventory levels according to the Table 2, row 1 solution results in the reduction of the CST to one month, a substantial improvement from the current base case situation. Furthermore, the recoverability of the supply chain is improved. As shown in Figure 16, Serviceable inventory recovers in half the amount of time as the base case, and regional inventory begins to recover almost immediately.

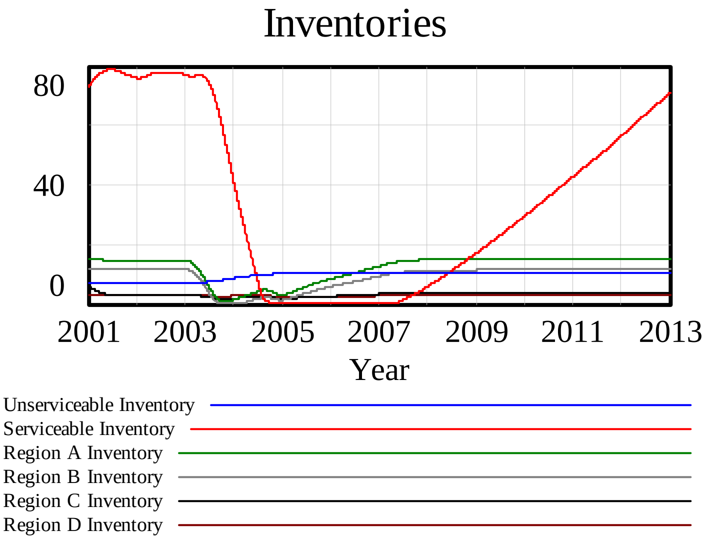


Figure 16: Case 3 Inventory Levels with an Increase in Demand in 2003; Stocking is Optimized and the CST is 30 Days

Despite the extent to which the responsiveness of the supply chain improves by implementing the inventory optimization methodology, additional improvements are warranted due to the importance of meeting demand. Therefore, the next three cases assume the OEM can reduce its assembly time from 180 days to 120 days for new production and from 90 days to 60 days for overhaul. The first case assumes no safety stock in the manufacturing tiers. Figure 17 shows that this one change, although only reducing the overall PLT by two months, allows the recovery time of Serviceable inventory to decrease by an entire year. Similarly, regional inventories also recover a year earlier than the base case. Additionally, as noted previously in Table 3, decreasing this assembly time reduces Working Capital substantially, and this savings can be reinvested in safety stock levels to further improve the readiness of the Government supply chain.

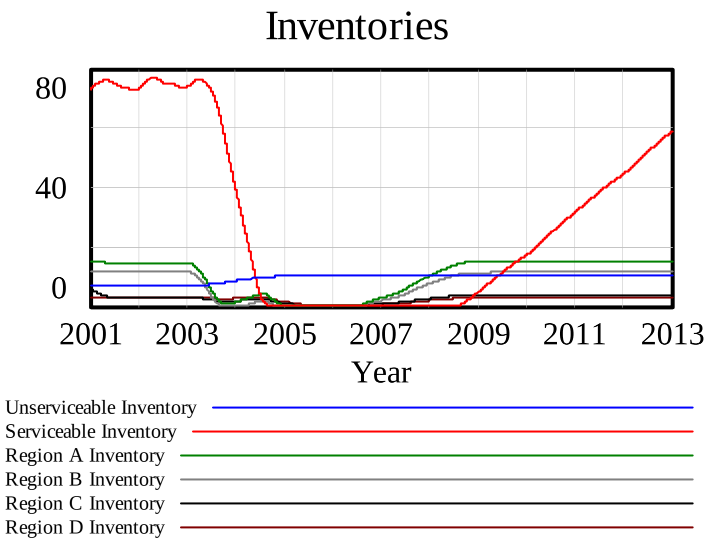


Figure 17: Case 4 Inventory Levels with an Increase in Demand in 2003; No Stocking in the Manufacturing Tiers Exists

Applying some of the Working Capital savings towards inventory optimization further helps the recoverability of the supply chain from sudden increases in demand. Figure 18 shows that the application of inventory management policies across the supply chain produces important benefits to the customer. For example, maintaining safety stock levels as in Figure 9 allows the Serviceable inventory to recover a year earlier than the previous scenario. Regional inventory in this case begins to recover almost immediately. These are notable results compared to the base case, especially considering the Working Capital is still reduced from the original scenario.

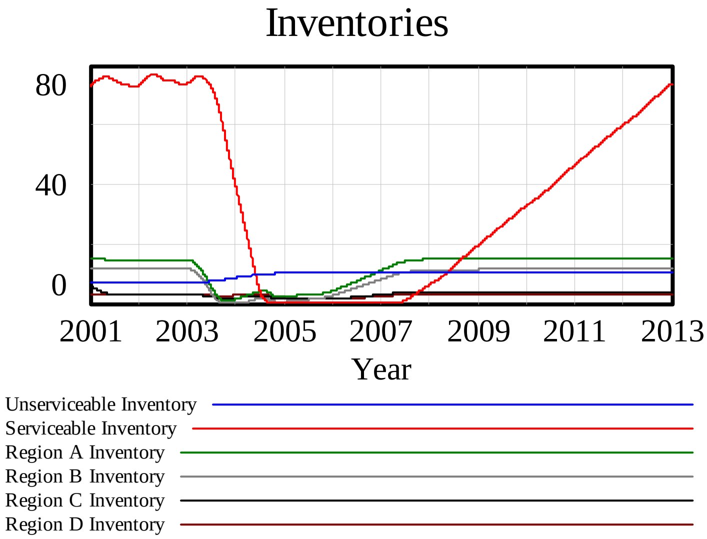


Figure 18: Case 5 Inventory Levels with an Increase in Demand in 2003; Stocking is Optimized and the CST is 240 Days

Finally, applying additional Working Capital to inventory optimization policies permits the CST to be reduced to 30 days, as noted in Table 4. Employing the Inventory Analyst solution shown in Table 4, row 1 to the stock levels across the supply chain substantially benefits the supply chain recovery rate from a sudden increase in demand. The Serviceable inventory levels begin recovery in a matter of months, and the regional inventory levels begin recovery immediately. The new demand level does not overwhelm the supply chain, and the entire system stabilizes by the year 2013. Working Capital in this case is still reduced from the base case. This situation creates a supply chain that is much better suited to handle the volatility of demand and long lead times that are inherent in the aviation industry.

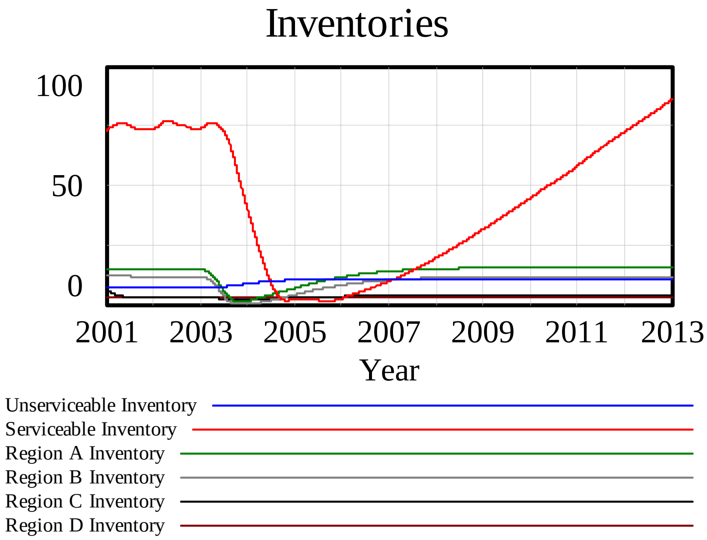


Figure 19: Case 6 Inventory Levels with an Increase in Demand in 2003; Stocking is Optimized and the CST is 30 Days

6. Conclusions

Government supply chains for high-value aviation spare parts have experienced considerable problems in providing adequate and stable supply. Supply uncertainties such as long lead times and uncertain demand levels are a fundamental part of the problem. Holding larger and larger inventories of final goods is a very expensive method of counteracting this problem and is not fiscally viable. An improved alternative strategy can be developed by creating a push and pull boundary of optimized safety stock in the tiers of the manufacturing supply chain. This approach not only increases recovery rates from sudden shifts in demand, but also reduces the amount of working capital invested to achieve desired service times. A simulation model of the extended supply chain has been used to demonstrate that push-pull boundaries enhance the ability of the supply chain to be adaptive and responsive, and to efficiently mitigate the risks of forecast errors prevalent within the Government requirements determination process.

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