The Dynamics of Multi-Tier, Multi-Channel Supply Chains for High-Value Government Aviation Parts

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 have been plagued recently by shortages. A system dynamics model has been developed of an aviation supply chain producing a major sub-assembly composed of eight components, each component coming from a three tier supply chain. These components are used in new production as well as overhaul of damaged parts. It was found that in the face of varying demands substantial bullwhip was produced and that it became especially pronounced at the lower levels of the supply chain. Moreover, it was shown that the government ordering process is extremely sensitive to common data errors such as the production lead-time and that production constraints, not included in the ordering algorithms, created deep and prolonged shortages. Ongoing research is developing improvements to the formulation of the ordering process and developing optimum inventory strategies for creating push-pull boundaries within the manufacturing process.

Introduction

Manufacturing has changed. Companies that were once known as automakers or aircraft manufacturers are now more properly viewed as integrators or assemblers. Parts and major sub-assemblies are now out-sourced and are planned to arrive just in time at the assembly plant for integration into cars, airplanes and other major products. Consider, for example, the new Boeing 787 Dreamliner. The wing comes from Japan, the movable trailing edge of the wing is produced in Australia, the fixed and movable leading edge of the wing is produced in Oklahoma, the wing tips are produced in Korea, the center fuselage is made in Italy, the landing gear is made in the UK, and the landing gear doors are made in Canada. (Avery, 2007) Automakers and electronic equipment manufacturers have similar extended supply chains. Sub-assemblies and major components come from a vast geographic network that is both broad and deep.

In these supply chains, major sub-assemblies are shipped to the OEM by hundreds of first tier suppliers, but these first-tier companies are just the tip of the supply chain iceberg. For each major component or sub-assembly, there is a multi-tier supply chain that may extend back, for example, from a first tier precision machining company, to a second tier casting company to a third tier raw material provider. Moreover, each major sub-assembly such as a transmission or landing gear is made from multiple parts, each provided by a separate channel through a multi-tiered supply chain. Thus, most, if not all, major sub-assemblies are the product of a multi-tier, multi-channel supply chain. It is important to note that in the supply chains for government aviation parts, overhaul is a major source of supply. When damaged parts are returned for overhaul, they require some of the components from the multi-channel, multi-tiered supply chains. Overhaul thus creates demands in addition to those of the new production process. Shortages of components thus affect both new production and overhaul of high-value aviation parts.

Performance problems often arise in the lower tiers of these supply chains. For example, during 2004, the lead-time for both aerospace steels and titanium grew from roughly three months to over a year. Lead-time for titanium continued to grow and reached roughly seventy weeks in 2005 and 2006. These developments threw the supply chains for aviation assemblies such as transmissions, landing gears, etc. into disarray. Somewhat similarly, the resurgence of the aviation industry has led to growth in orders that exceeded the production capacity of many lower tier suppliers, and backorders are often common. For example, demands for aerospace fasteners today exceed production capacities. As a result of raw material delays and capacity constraints, inventories of many high-value spare parts for government aviation have declined to very low levels and have had difficulty recovering. Similarly, supply chain issues of one type or another have delayed both the Airbus 380 and the Boeing 787. While numerous studies have suggested a reformation of the Government supply process that was implemented decades ago, Gansler and Luby (2003), Abramson and Harris (2004), and Folkeson and Brauner (2005), the same underlying process and associated problems tend to plague the system in place today.

A research program was initiated to investigate the dynamics of multi-tier, multi-channel supply chains providing high value aviation parts to the Government. The objectives were to: examine the impacts of the Government ordering process under a variety of time-varying demand conditions; assess the impacts on supply chain performance of inaccurate data in the calculation of the recommended buys and overhaul; examine the bull-whip effect in the multi-tiered, multi-channel supply chain; assess the potential for cross-coupling of problems among the multiple channels; and examine supply chain performance in the face of production capacity constraints not included in the supply requirements determination process of the government.

Analytical Approach

System Dynamics is an appropriate technique for analyzing complex multi-tier, multi-channel supply chains. System Dynamics has been used to analyze supply chains from its very beginning as a modeling and simulation tool for policy analysis. Forrester's (1958) groundbreaking article in the Harvard Business Review demonstrated fundamental supply chain dynamic behavior such as how small changes in retail sales and promotional activity can lead to large swings in factory production, i.e., the so-called bullwhip or Forrester effect. Forrester (1961) also included a supply chain model and demonstrated various modes of behavior. Forrester's models included factory, distribution and retail tiers in the supply chain but no suppliers to the factory. More recently, Sterman (2000) has addressed supply chains with several models and case studies. Again these are forward looking supply chains from factory to customer with perhaps a single supplier. Huang and Wang (2007) addressed the bullwhip effect in a closed loop supply chain using a simple model based on Sterman's (2000) structure. Simchi-Levi (2008) and Lee (1997) address bullwhip from an analytical perspective. Schroeter and Spengler (2005) addressed the strategic management of spare parts in closed-loop supply chains. Angerhofer (2000) presents a thorough discussion of system dynamics modeling in supply chain management. Killingsworth, Chavez, and Martin (2008) address the government ordering process within a system dynamics model but does not include an extended supply chain. The intent of the current research is to capture the actual algorithms of a government procurement process, embed this procurement or ordering process within a system dynamics supply chain model incorporating multiple tiers of suppliers and multiple channels of components, and assess the impacts and performance of the extended enterprise supply chain.

Model Description

The overall supply chain system providing high-value aviation spare parts is shown in overview in Figure 1. This supply chain extends from raw material to final customer. Demand arises from aircraft located in four regions of the world. Demand in each region is driven by the number of aircraft in the region, monthly flight hours, and failure rate per part per flight hour. Each region has an inventory of key spare parts, and these inventories are replenished from a central distribution inventory. Supply of parts comes from three sources: production of new items, commercial overhaul of damaged parts, and government depot overhaul of damaged parts. Each type of production requires that a number of parts be integrated into the major sub-assembly. In general, the overhaul process requires fewer component parts than new part production. The

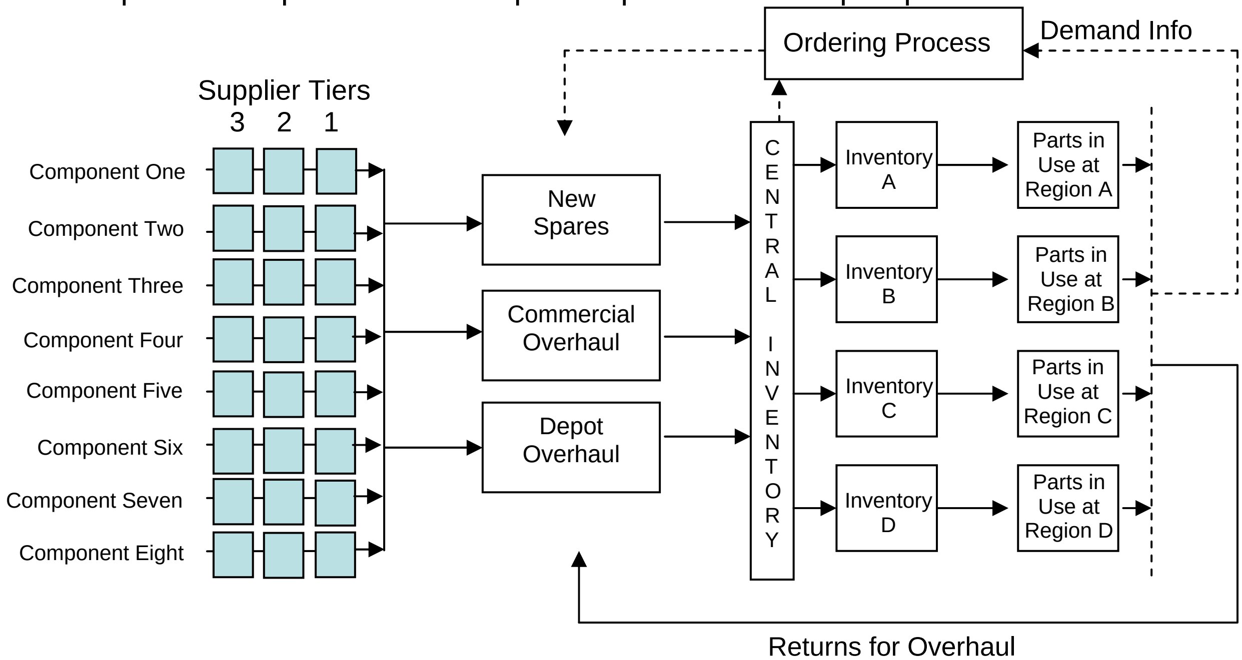

Figure 1: Overview of the Multi-Tiered, Multi-Channeled Supply Chain Model

component parts are each produced through a three-tier supply chain. Each of these chains typically has a different manufacturing time at each tier, and each channel has a different total production time. The overall supply process is managed in a feedback fashion by the government's ordering or requirements determination process. This process is at the heart of many government and defense supply chains for high-value parts. (Rosenman, 1964) This computerized process is used to determine the recommended buys for new parts and the recommended number of parts to undergo repair and overhaul. The supply chain control system compares current levels of inventory, including due-ins and due-outs, with anticipated needs to calculate recommended buys and repairs. Since the procurement of new spares and the overhaul of damaged spares leads over time to changes in inventory, the system truly functions in a feedback control fashion to manage the supply chain. (Killingsworth, Chavez, and Martin, 2008)

Figure 2 provides a more detailed view of the flows present in the model. It is important to note that many, if not the vast majority, of these aviation supply chains for high-value government spare parts operate in a sequential fashion, with little information sharing and little risk taking within the supply chains. For example, the government will request a proposal from the OEM to provide a certain number of the major assemblies. The OEM will respond with a proposal, and after negotiation, will be awarded a contract. The OEM will then request a proposal from the first tier suppliers to provide their components. A proposal will be submitted, negotiated, and the OEM will award a contract to the first tier suppliers. These first tier suppliers will then turn to the second tiers and repeat the same process. The second tiers will only then place an order with the third tiers for, in many cases, the necessary raw material. Hence many months can go by before the order for raw materials is placed, and recently, many months then go by before the raw material is received. This sequential structure is built within the model. Moreover, the first, second and third tier suppliers are very risk averse and maintain essentially zero inventory of both their inputs and outputs. Purchasing of inputs and production of output only occurs in the presence of a contract or purchase order.

Several levels of calculation are incorporated into the Supply Chain Control Center to determine recommended buys and repairs. (Killingsworth, Chavez, and Martin, 2008) This computerized requirements determination process is embedded in many government supply databases. Within the determination process, the recommended procurement action for new spare parts is calculated by taking the difference between the procurement reorder point and the total available net assets, and then adding the procurement cycle requirement, the inventory necessary to meet demands until the next scheduled order (see Figure 3). Total net assets are calculated from due-ins from procurement and repair plus inventories, less due-outs. The procurement reorder point is based on reserves and safety levels. Orders that are placed with the OEM enter production subject to a maximum production rate and availability of all of the required components. Production is completed after a manufacturing lead time. These parts then flow into serviceable inventory.

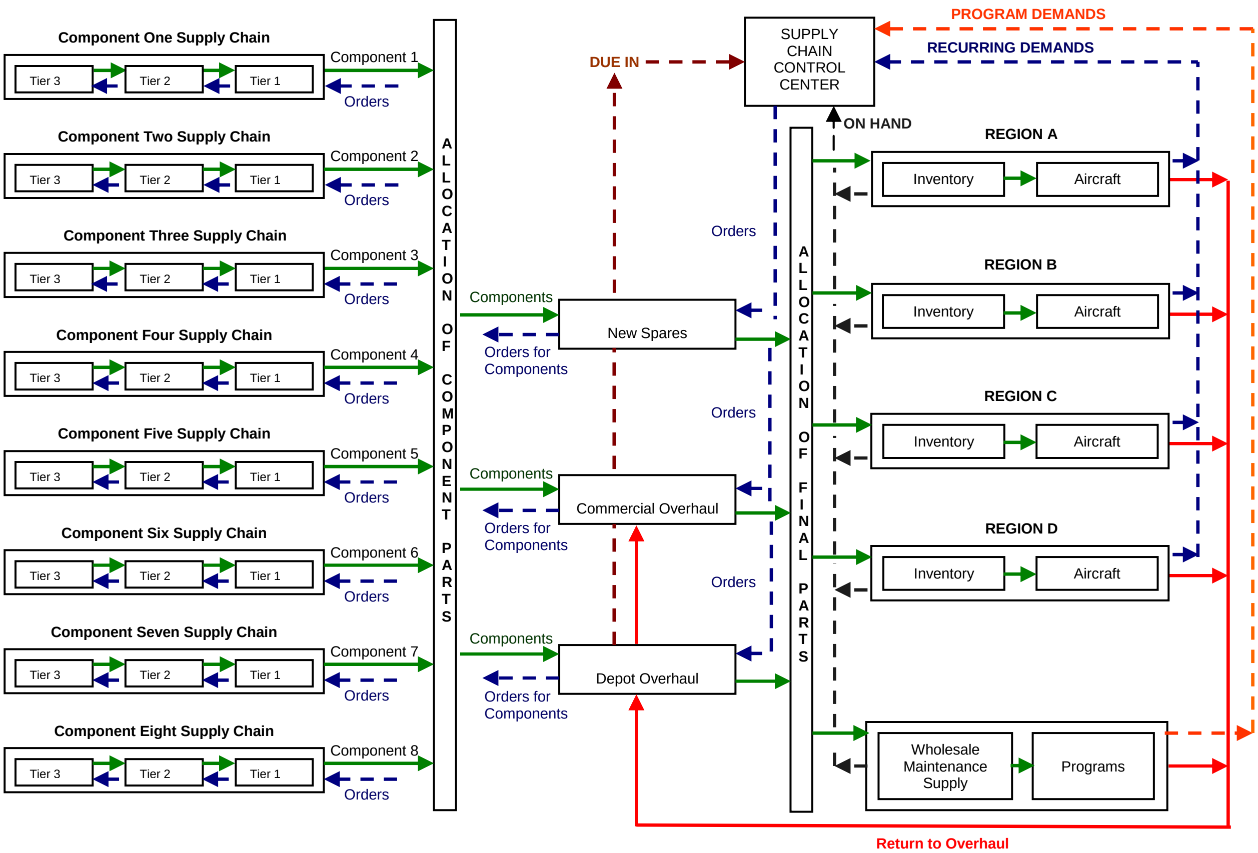

Figure 2: Detailed Overview of Model Flows

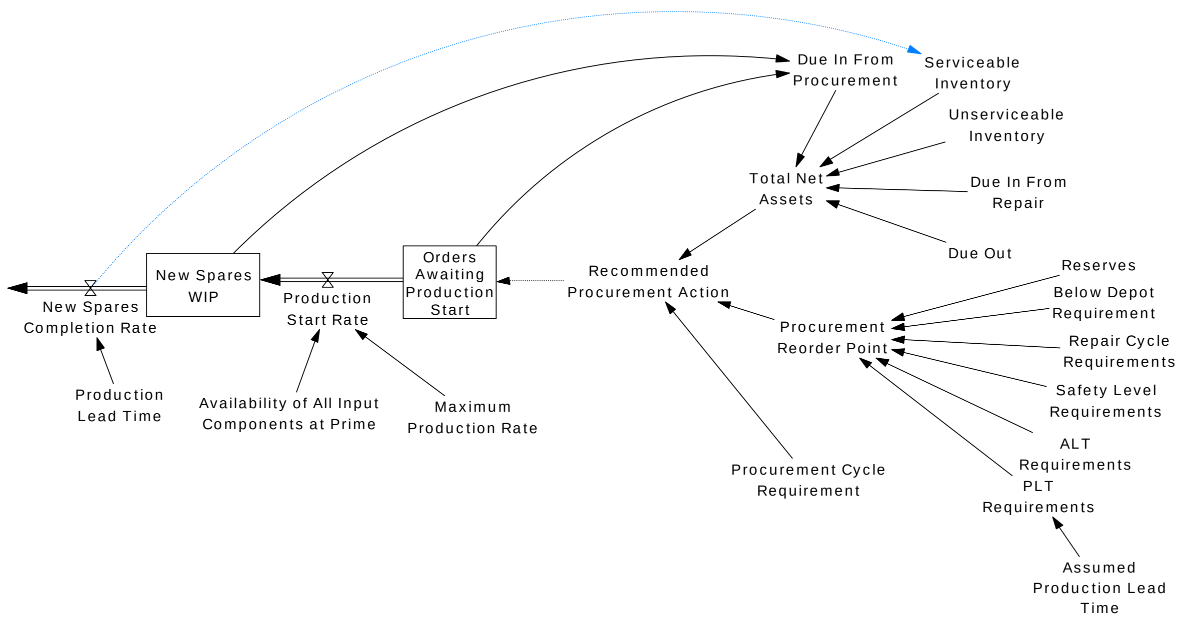

Figure 3: Recommended New Spares Procurement Action

In a separate calculation, the recommended repair action is determined. It must be noted that repair and overhaul can only be conducted if there is a damaged part available to be overhauled. The maximum recommended repair action is calculated by subtracting the assets available for repair, including overhaul and procurement work-in-progress less due-outs, from the repair action point, calculated with reserve levels and safety requirements. This repair action point is largely driven by historical demands. The maximum recommended repair action, however, is then limited by the unserviceable inventory on hand (see Figure 4). The potentially constrained repair order is allocated between government depot and commercial overhaul according to capacity levels at each location. The overhaul rates may be limited by production capacity levels. As inventory is repaired, it is shipped to serviceable inventory available for issue.

Once orders are placed for overhaul and new production, orders are then placed with the first tier suppliers for the components necessary to assemble the final product. Figure 5 illustrates the model structure for commercial overhaul. Similar structures exist for depot overhaul and new spare production. It is important to note that the overhaul process can only begin if necessary components parts are on hand.

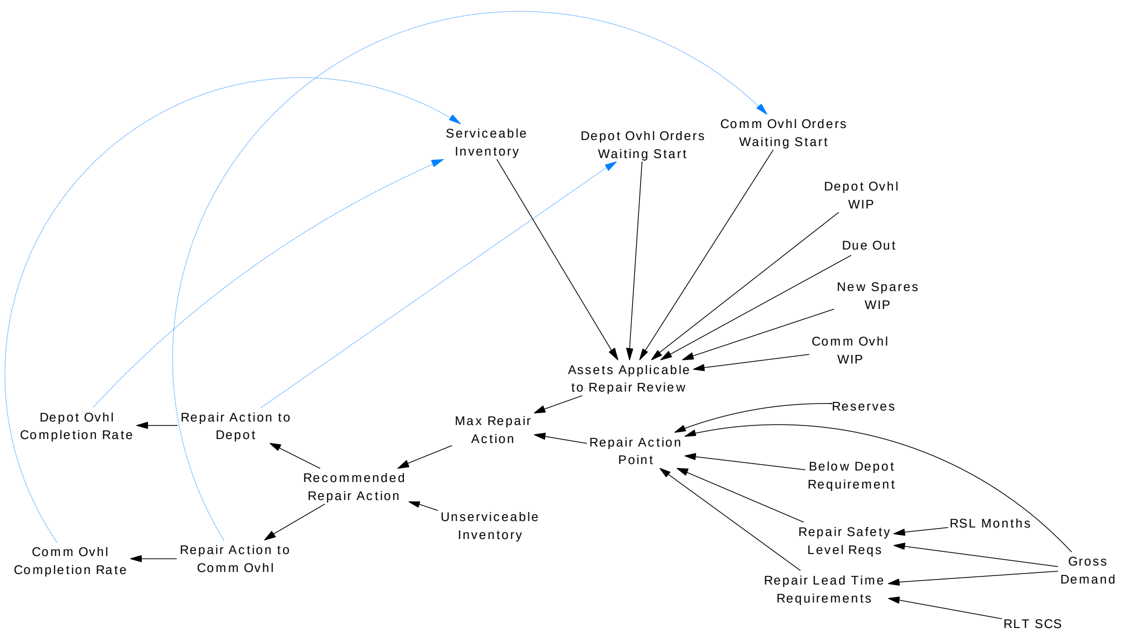

Figure 4: Recommended Repair Actions

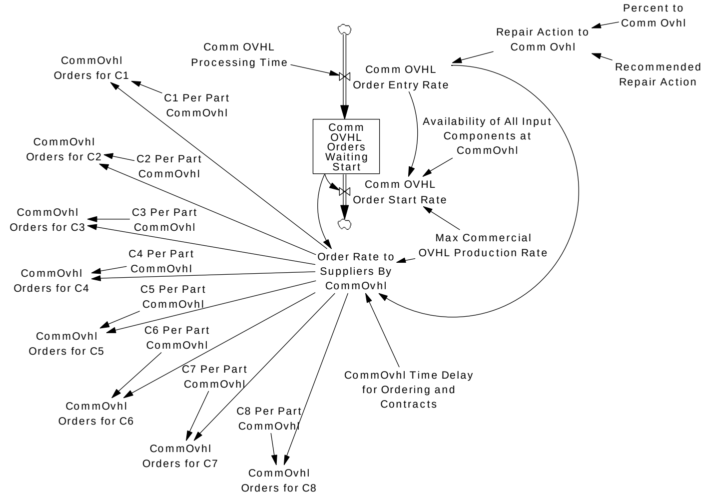

Figure 5: Order Placement Process to Supply Chain Tiers

The orders that originate in Figure 5 at the OEM or overhaul sites flow to the first tier suppliers. These suppliers then place orders with the second tier suppliers, who, in turn, then place orders with the third tier suppliers as shown in Figure 6. Second tier production can only begin if there is inventory available from the first tier such as the raw material. Similarly, production at the first tier can only begin if there is inventory of output from the second tier. Each tier is dependent upon the previous one to complete the process, and each level may be limited by a production lead time of another supplier.

As the components are shipped to new production, commercial overhaul or government depot overhaul, they flow into inventories at these sites. The total availability of components at these locations is determined by the minimum inventory level (see Figure 7). This availability value then becomes a factor in the determination of the production and overhaul start rates, seen previously in Figures 3 and 5.

Upon completion of orders through the overhaul and procurement processes, the products are shipped to the central inventory site and then to one of four regional inventories. The parts are pulled from these inventories and placed into service on an aircraft. The damaged or worn parts that are removed are returned for repair, less a percentage that are scrapped or not returned by the field. The returned parts enter the unserviceable inventory on-hand and then enter the overhaul process.

Analysis and Simulation Results

Key objectives of the analysis were to: (i) assess the performance of the government's requirements determination process in the presence of a multi-channel, multi-tier supply chain; (ii) evaluate the likelihood of the bull-whip effect being produced in the supply chain and the impact on lower tier suppliers; (iii) determine the sensitivity of the supply control to inaccurate data and (iv) evaluate impacts of real-world production and overhaul capacity constraints. The model described has been parameterized for specific high value parts and has been used to simulate the behavior and performance of the requirements determination process and the supply chain for these particular parts. The following cases are presented with a simulation time covering 2001-2012:

Case 1: Constant demand;
Case 2: Step up in demand in 2003;
Case 3: Oscillating demand;
Case 4: Error in PLT resulting from an increase in PLT at a raw material supplier. Data error persists for one year; and
Case 5: Production constraint limits production at a first tier supplier.

Cases 1 and 2 were used both in the validation of the model and to verify that the requirements determination process generated appropriate new procurement and overhaul orders in response to constant demand and a step-up in demand. These two cases also enabled assessment of the behavior of the ordering and production process in the multi-tier, multi-channel supplier network. Case 3 was conducted to determine whether the governmental computerized ordering process and related supply chain exhibited the bullwhip effect and to examine the impacts on the lower tier suppliers. Because numerous reports, for example, GAO (1981) and GAO (July 2007), have indicated that certain data, such as production lead-time, used in the ordering process is often incorrect, Case 4 investigates the impact of incorrect production lead-time on the ordering process and supply chain performance. Moreover, because the governmental

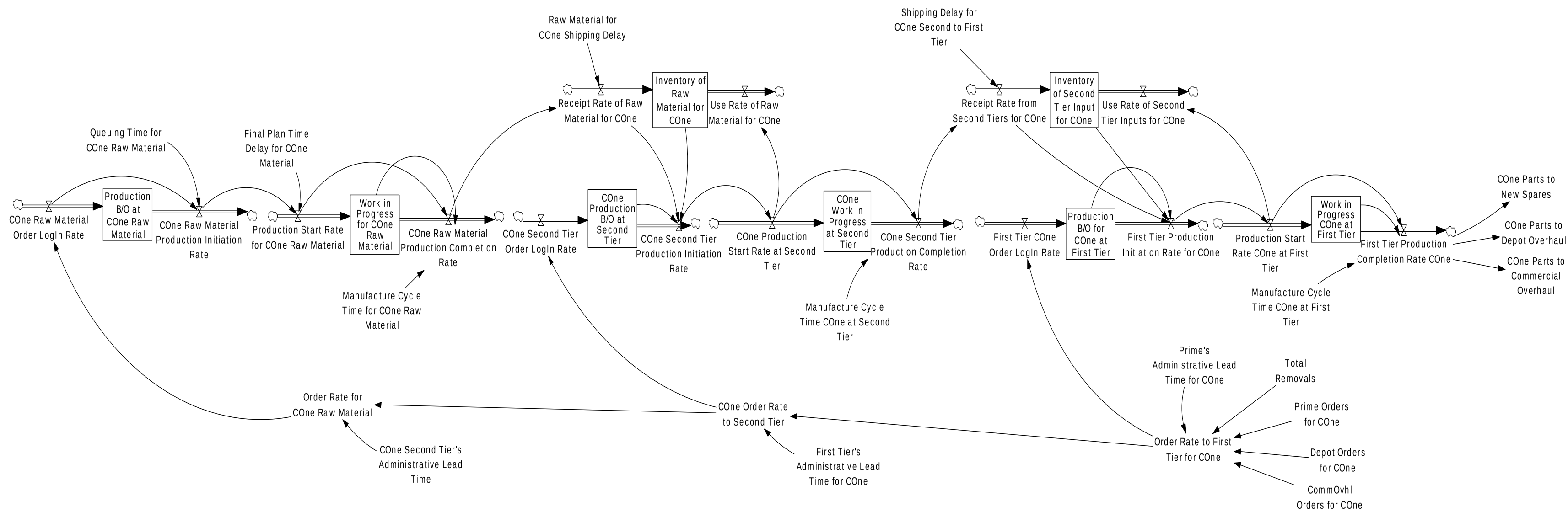

Figure 6: Supply Chain Tiers for Component One

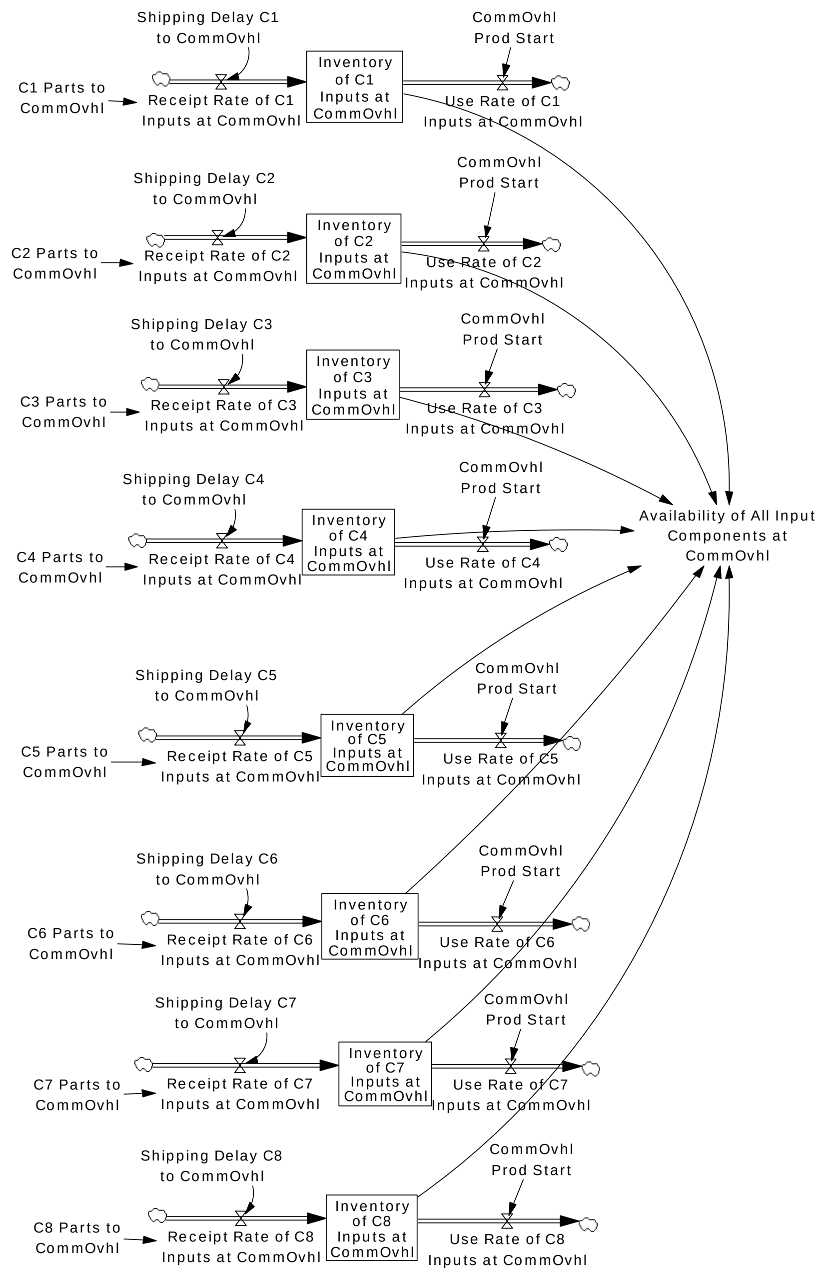

Figure 7: Availability of Components for Assembly

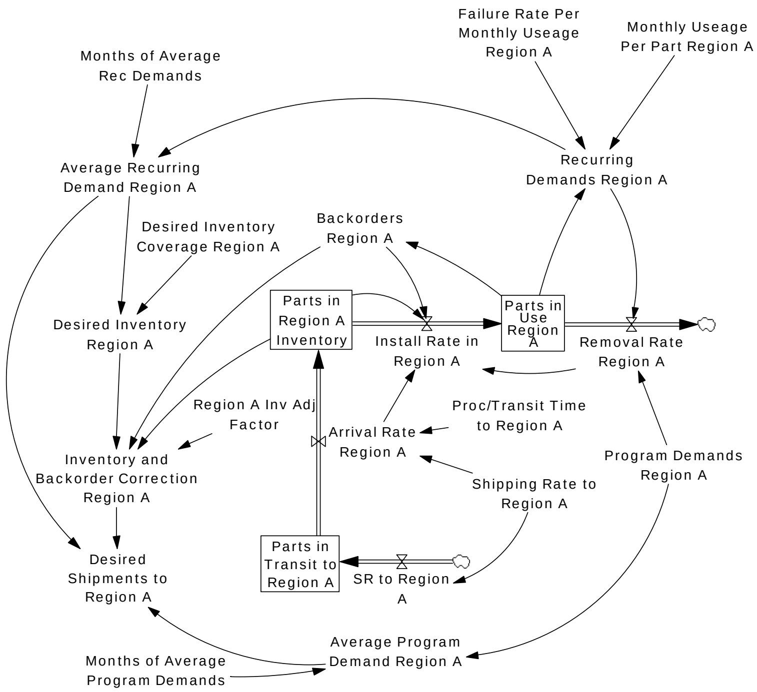

Figure 8: Region A Demands and Returns

ordering process does not include the potential for production capacity constraints, Case 5 examines the behavior of the supply control process and the ability of the system to meet rising demand in the presence of capacity constraints. Finally, Case 6 examines a "real world" scenario involving shifting demand, production constraints, and data errors.

Case 1 assumes constant demand of 14 units a month (divided between the four regions – Region A (7 units/mo), Region B (5 units/mo), Region C (1 unit/mo), and Region D (1 unit/mo)) as depicted in Figure 9. Other key assumptions include no limit on production or overhaul rates, an overall production lead time of 22 months, and a repair lead time of 11 months. The overall production lead time is calculated as the maximum lead time of the eight components plus the production lead time and administrative lead time at the primary supplier. The lead time of each component, that is, of each channel, is determined to be the sum of the shipping delays, the manufacture lead times, and the administrative lead times for each tier. The first four cases assume that four components are used for new spare production only and have a common overall lead time of 12.2 months. The other four components are used for both overhaul and new spare production and have a common overall lead time of 8.2 months. For new spare production, the OEM requires 9.8 months for assembly and integration resulting in the 22 month overall PLT used in the requirements determination process. For overhaul, the depot and commercial overhaul facility require 2.8 months for integration and assembly yielding the 11 month overall RLT used in the requirements determination process. The assumed PLT and RLT for the ordering determination process are equivalent to the overall actual values in this case.

The simulation output from Case 1 is presented in Figures 9-15. Figure 9 shows the constant input demands. Figure 10 shows that the Central and Regional Inventory levels remain constant. Figure 11 shows that removals, shipments to regional inventories and production and overhaul rates are constant. The system establishes an equilibrium that is maintained throughout the simulation. Figure 12 presents the availability of component inventory at the OEM and the two overhaul sites. The somewhat surprising oscillation in the available components at Prime stems from the procurement process. Figure 13 shows that when the Total Net Assets dip below the Procurement Reorder Point, a procurement action occurs for a period of time. The procurement action ceases because the procurement action leads to orders that create due-ins increasing Total Net Assets. Once a procurement action is initiated, an order to the supply chain tiers follows as shown in Figure 14. Figure 15 shows how these pulsing orders thus create highly variable input inventory at the OEM's even in the face of constant demands. The repair process is more stable because repair actions are limited by the requirement for damaged or worn parts that maintain a constant flow due to constant removals. This stability is shown in Figure 14.

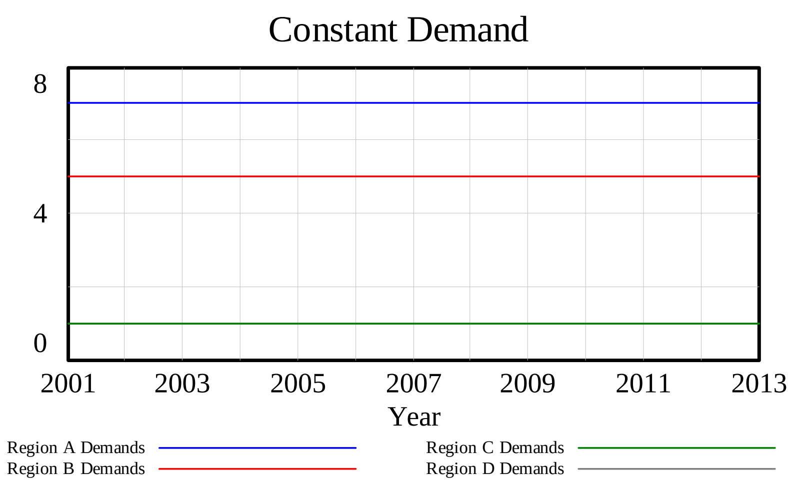

Figure 9: Constant Demand Levels

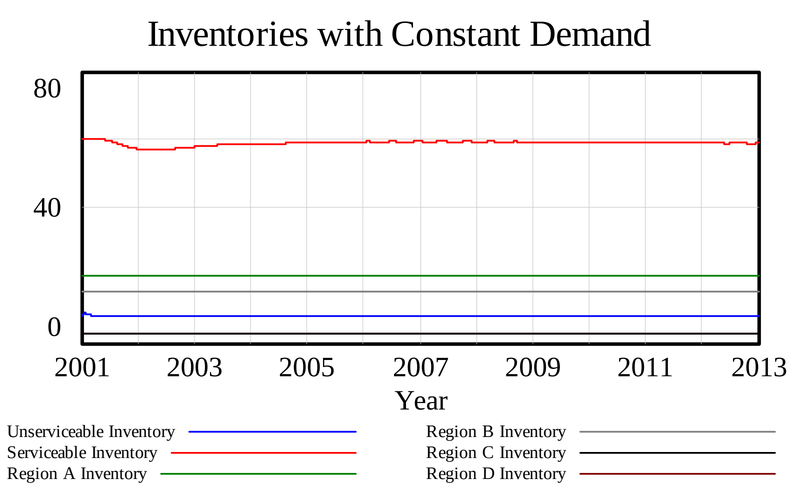

Figure 10: Inventories with Constant Demand

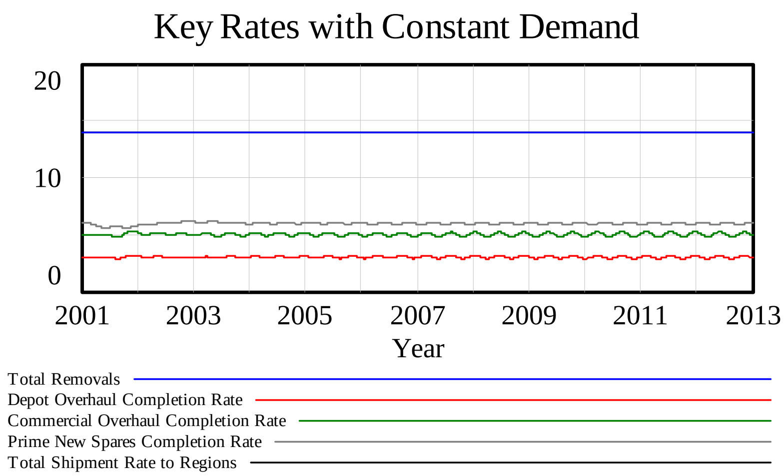

Figure 11: Key Rates with Constant Demand

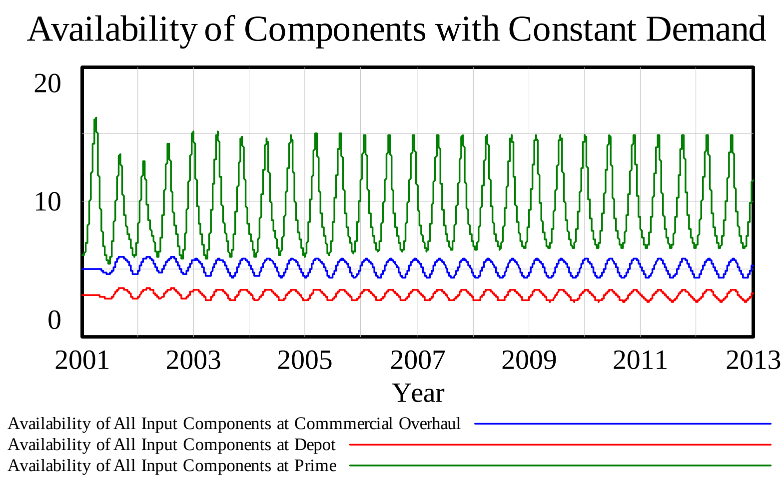

Figure 12: Availability of Components for the Overhaul and Production Processes with Constant Demand

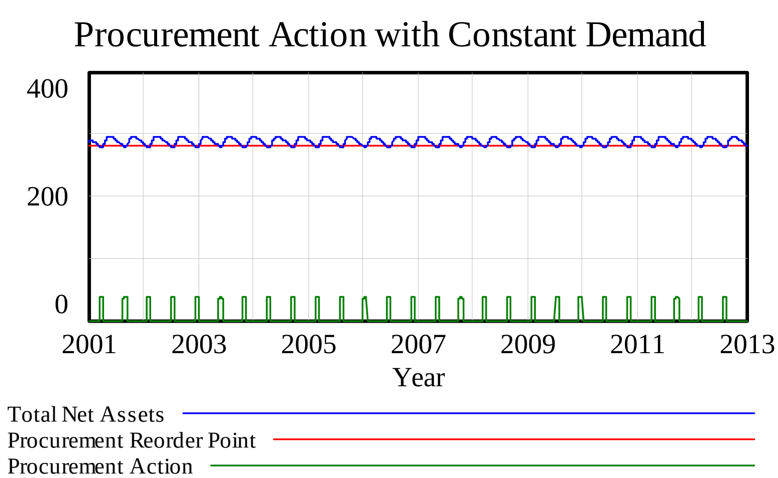

Figure 13: Procurement Action with Constant Demand

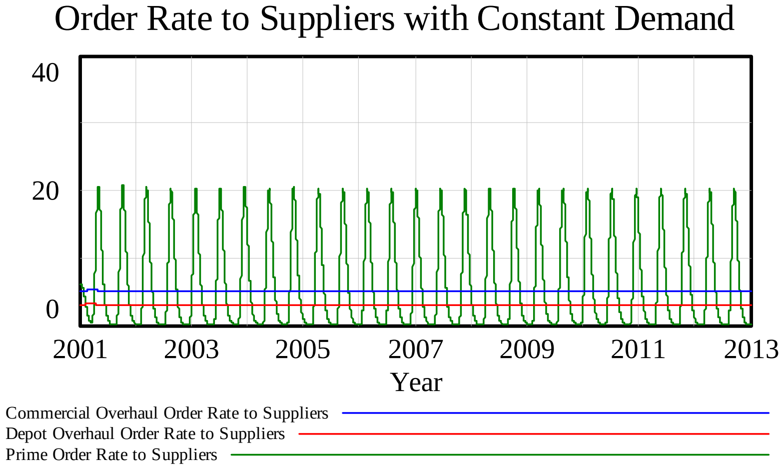

Figure 14: Order Rate of Components for Overhaul and Procurement Processes with Constant Demand

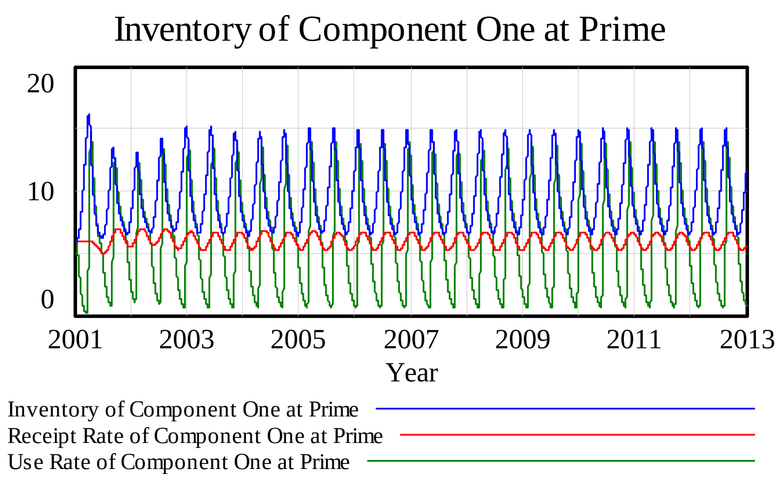

Figure 15: Inventory of Component 1 at OEM with Constant Demand

Case 2 assumes a step increase in demand from 14 to 18 parts a month in 2003 (each region increasing demand by 1 unit per month), while holding all other assumptions the same as the steady state case. This case illustrates the typical growth in demand that has been seen for aviation parts within the past five years and also provides a basic determination of the recovery time of the system after a disturbance from equilibrium (Forrester, 1961). Figure 16 illustrates the input demands, and Figure 17 presents the serious impacts on the central and regional inventories. As may be seen, the central inventory is depleted for a period of nearly two years. This shortage occurs because of the long lead times in production and overhaul of high-value aviation spare parts. As may be seen in Figure 18, the new production rate increases in response to the higher demands, but overhaul rates are constrained by the number of unserviceable items on hand. Component availability presented in Figure 19 slowly grows to support higher levels of procurement and overhaul but does not grow fast enough to enable production to halt the depletion of inventory. Since the Procurement Reorder Point is largely determined by a twenty-four month average demand, the procurement process does not respond to the higher demand for at least a year. As may be seen in Figures 20 and 21, as the Reorder Point begins to increase in 2004 and 2005, it causes larger and more frequent orders for new spares. Since raw material is ordered last but used first in the supply chain, the increase in orders causes the raw material inventory at tier two to be quickly depleted and remain at very low levels (see Figure 22). The repair process is once again limited by the unserviceable inventory on-hand, as depicted in Figure 23, in which the repair action is equal to the unserviceable inventory, while the desired maximum repair is significantly higher. This constraint on the repair action therefore dampens the number of components utilized in overhaul and keeps this process relatively stable.

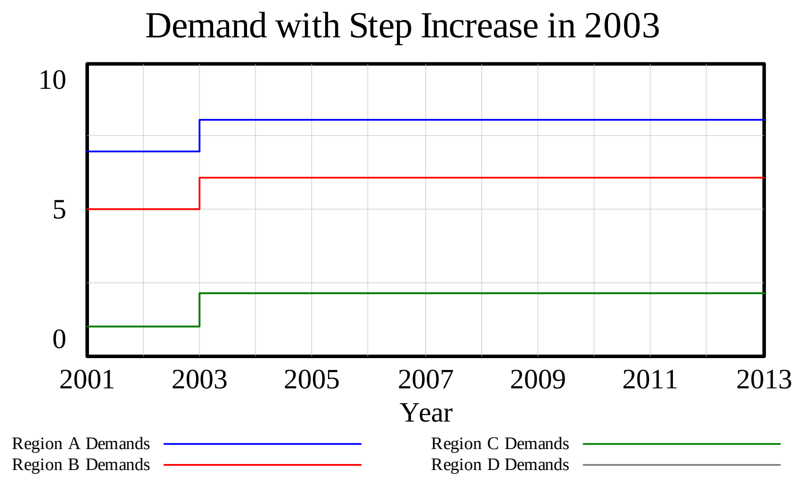

Figure 16: Demand Steps Up in 2003

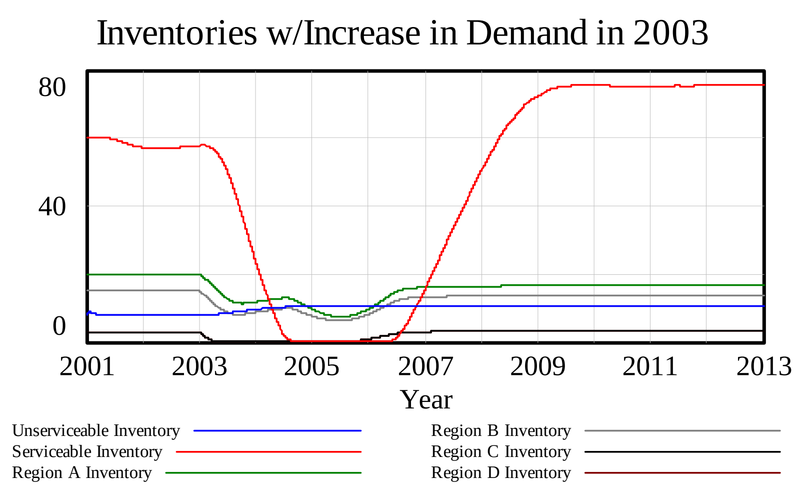

Figure 17: Inventories with a Step Increase in Demand

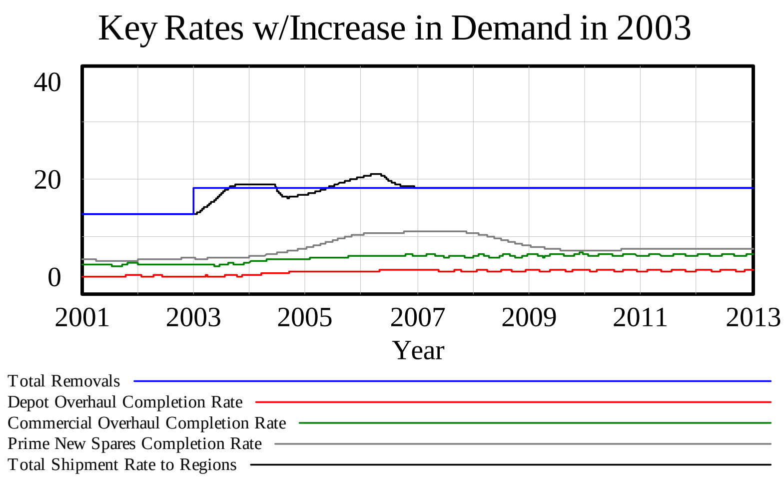

Figure 18: Key Rates with a Step Increase in Demand

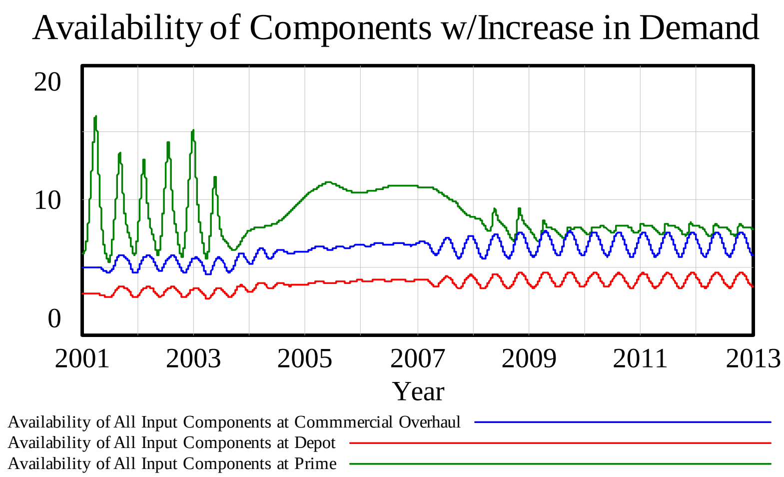

Figure 19: Availability of Components for the Overhaul and Production Processes with a Step Increase in Demand

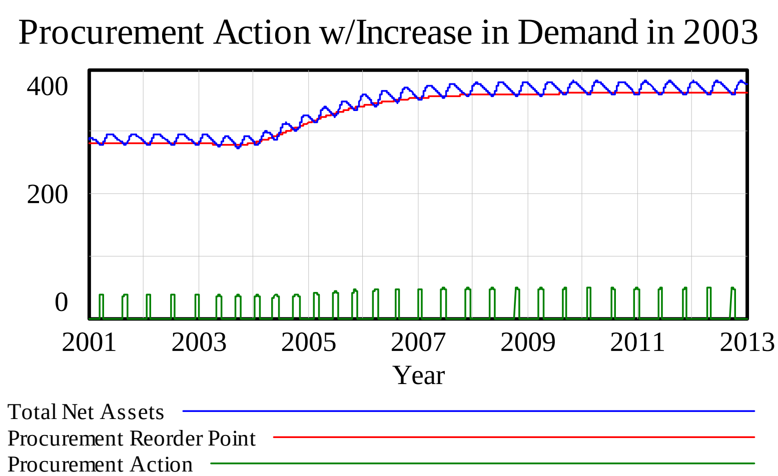

Figure 20: Procurement Action with a Step Increase in Demand

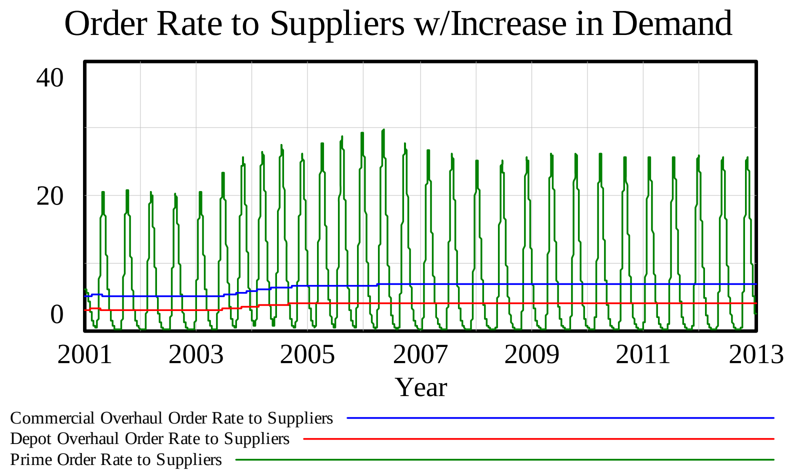

Figure 21: Order Rate of Components for Overhaul and Procurement Processes with a Step Increase in Demand

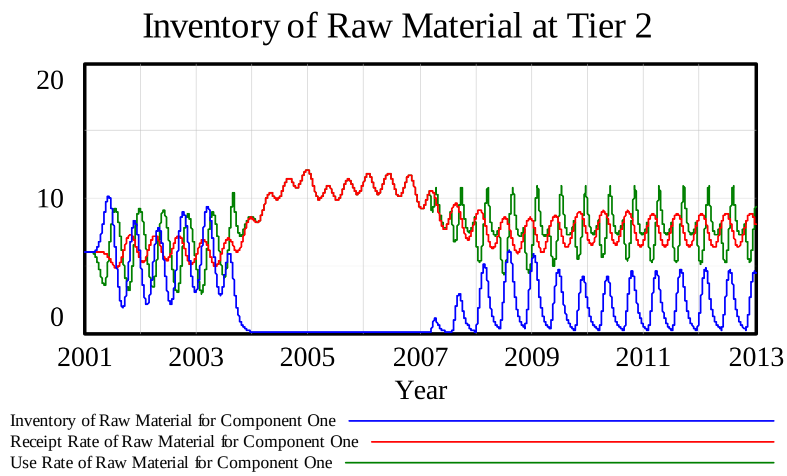

Figure 22: Inventory of Raw Material for Component One used in Overhaul and Procurement Processes with a Step Increase in Demand

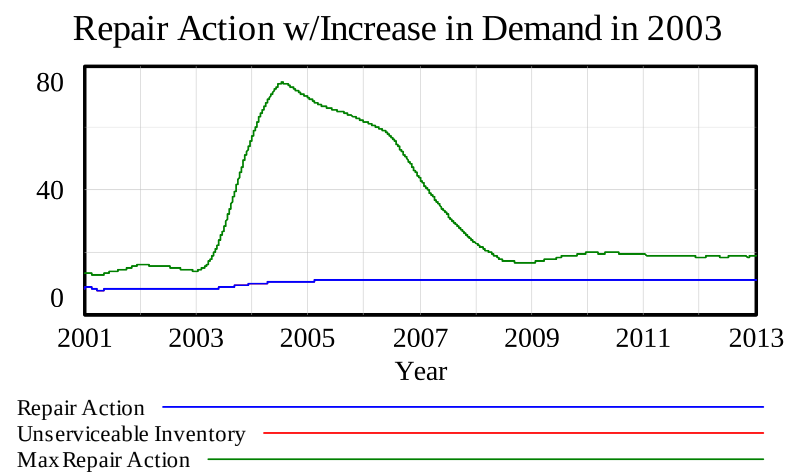

Figure 23: Repair Action with a Step Increase in Demand

To examine the potential for bullwhip effect in this extended supply chain, Case 3 assumes a ±20% sinusoidal oscillation in demand over a four year period. All the other key assumptions from Case 1 remain the same. Figure 24 presents the input demand assumptions and Figure 25 shows the considerable variation in inventories. The production and overhaul rates fluctuate, but the bullwhip is not severe. This is because of the sequential nature of the ordering process which does not include amplification but simply passing orders along the chain and because overhaul variation is limited by unserviceable inventory on-hand (see Figure 26). Availability of components is also affected by these fluctuations in demands, producing spikes in inventory levels that vary from the initial inventory level by as much as 90% (see Figure 27). This volatility is a result of the irregular procurement action, shown in Figure 28, which then causes the order rate of components to suppliers to fluctuate (see Figure 29). The order rate to suppliers also affects the inventory of materials in the supply chain tiers. Since the raw material supplier is the last to receive the order, this supplier is affected the most by the instability of the orders, causing the inventory levels at the second tier to suffer. Inventory levels grow as orders are placed, but almost completely diminish as orders slow down and materials are used; as a result, significant fluctuations ranging by as much as 100% of the initial inventory levels ensue (see Figure 30). Meanwhile, tiers closer to the customer are able to maintain some level of inventory at all times, but this level is still extremely unstable, varying again by about 100% for some short durations (see Figure 31). This volatile nature is also present in the repair process, although the extent of the variation in inventory levels is limited by the unserviceable inventory on-hand. In this case, however, the repair action is affected by both the limited unserviceable inventory at times and the recommended repair action at other times (see Figure 32). The bullwhip effect is therefore still quite evident in the supply chain tiers, as indicated in the component inventory levels at commercial overhaul in Figure 33.

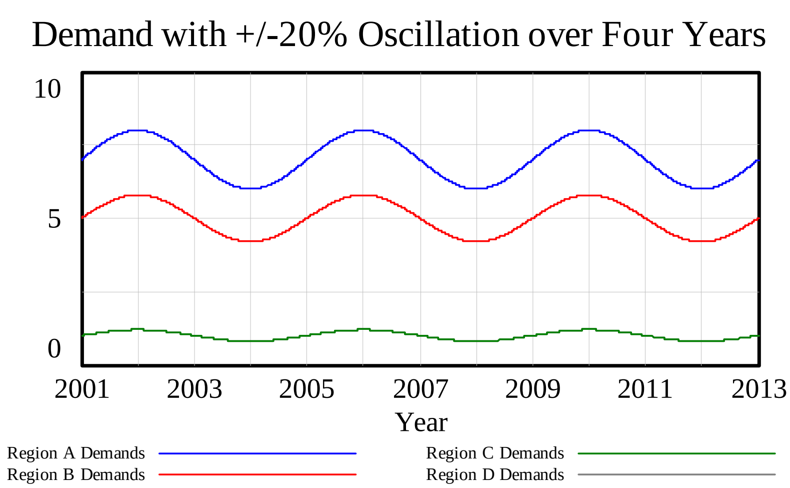

Figure 24: Demand with a 20% Oscillation and a 4-year Oscillation Period

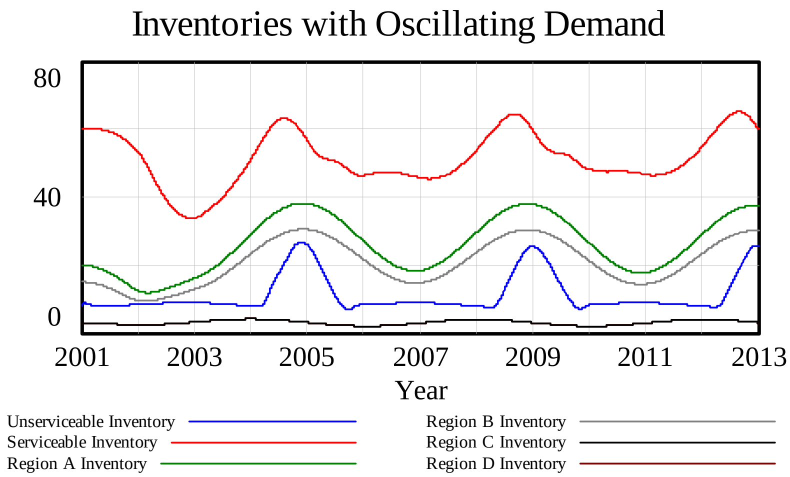

Figure 25: Inventories with a 20% Oscillation in Demand, 4-year Oscillation Period

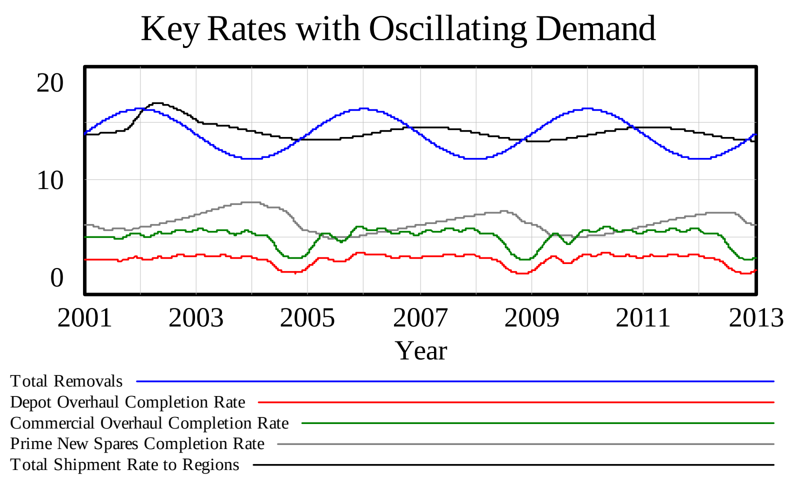

Figure 26: Key Rates with a 20% Oscillation in Demand, 4-year Oscillation Period

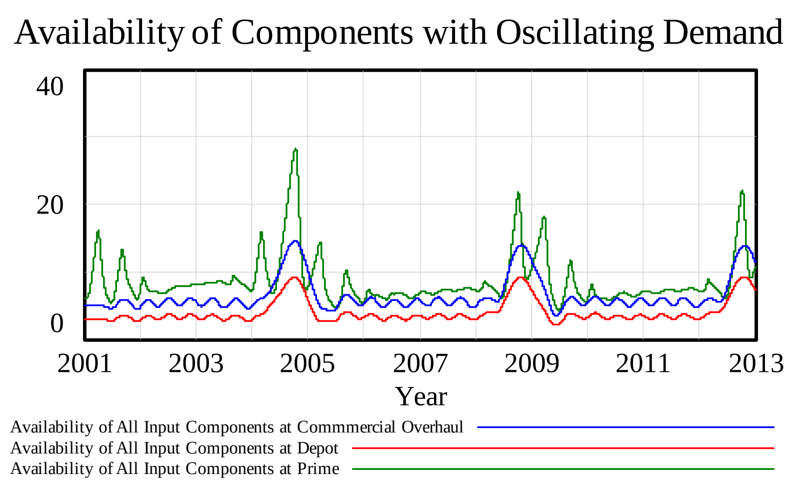

Figure 27: Availability of Components for the Overhaul and Production Processes with a 20% Oscillation in Demand and a 4-year Oscillation Period

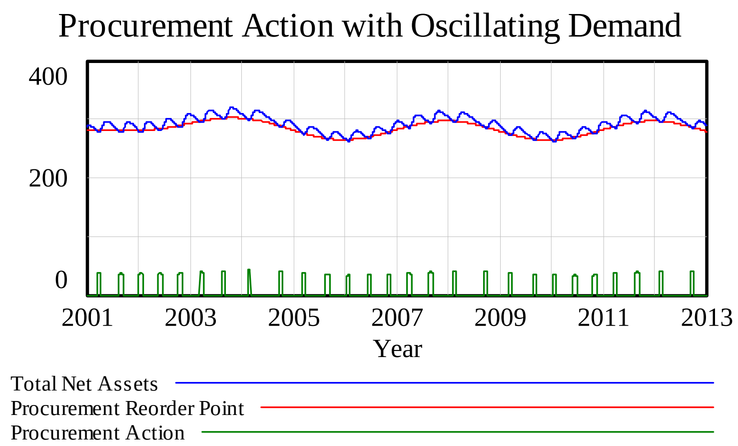

Figure 28: Procurement Action with a 20% Oscillation in Demand, 4-year Period

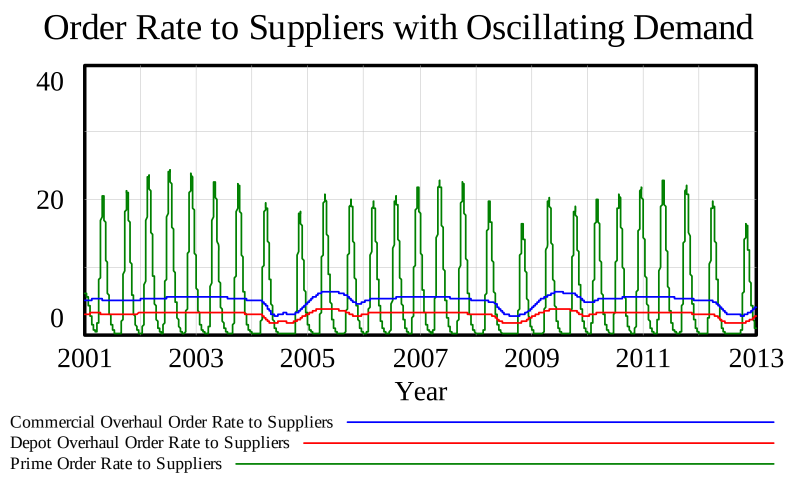

Figure 29: Order Rate of Components for Overhaul and Procurement Processes with a 20% Oscillation in Demand and a 4-year Oscillation Period

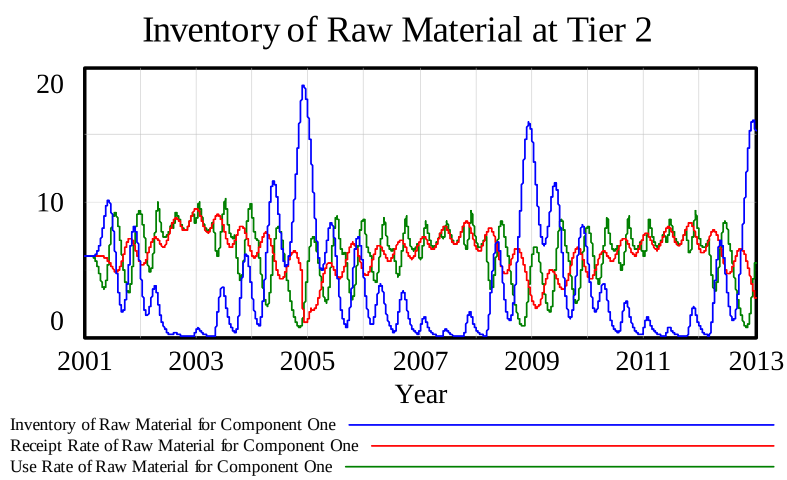

Figure 30: Inventory of Raw Material Component One used in Overhaul and Procurement Processes with a 20% Oscillation in Demand and a 4-year Oscillation Period

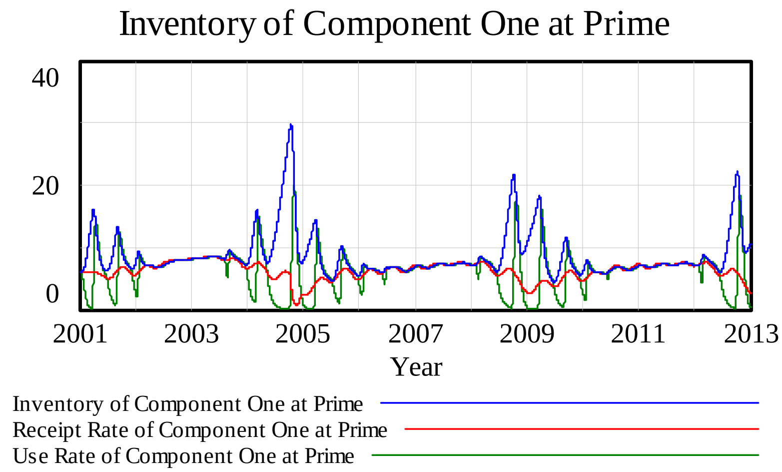

Figure 31: Inventory of Material used Procurement Process with a 20% Oscillation in Demand and a 4-year Oscillation Period

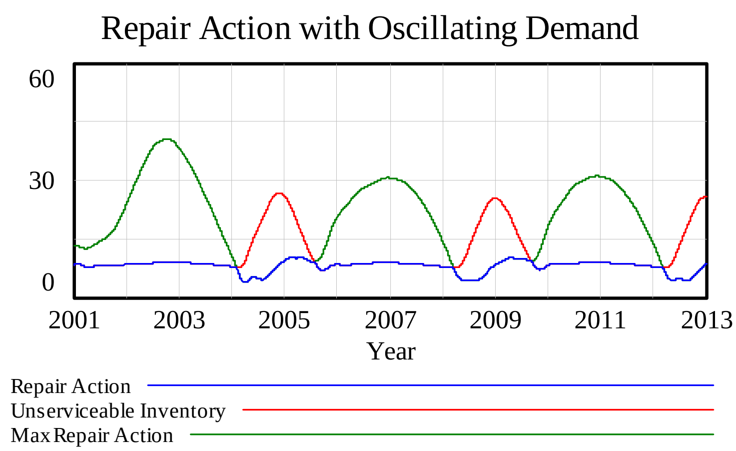

Figure 32: Repair Action with a 20% Oscillation in Demand 4-year Period

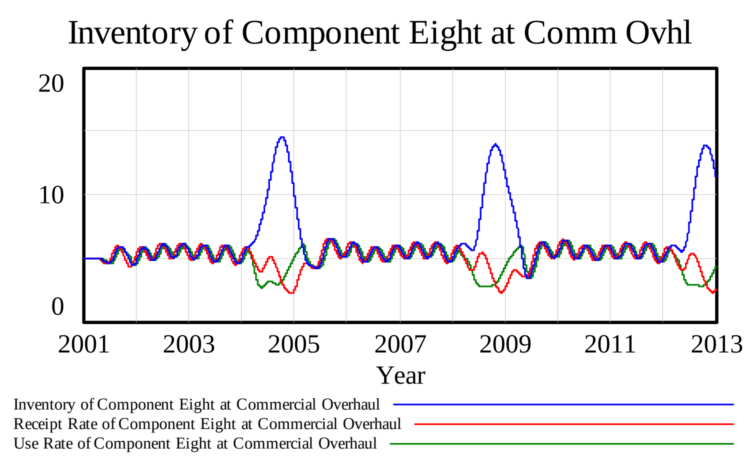

Figure 33: Inventory of Material used in Overhaul Process with a 20% Oscillation in Demand and a 4-year Oscillation Period

Assuming alternative periods for the oscillation in demand greatly affects the supply chain performance (Figure 34). Increasing the period from 2 years to 4 years to 8 years amplifies the bullwhip effect in serviceable inventory, as shown in Figure 35.

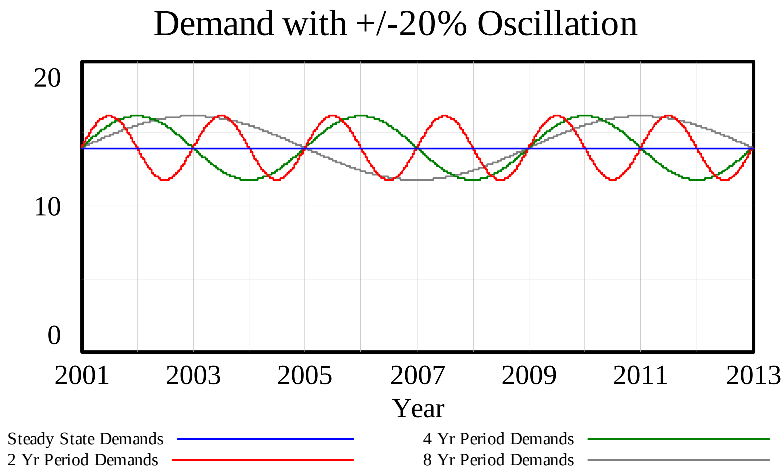

Figure 34: Demand with a 20% Oscillation and a 2, 4, and 8-year Period

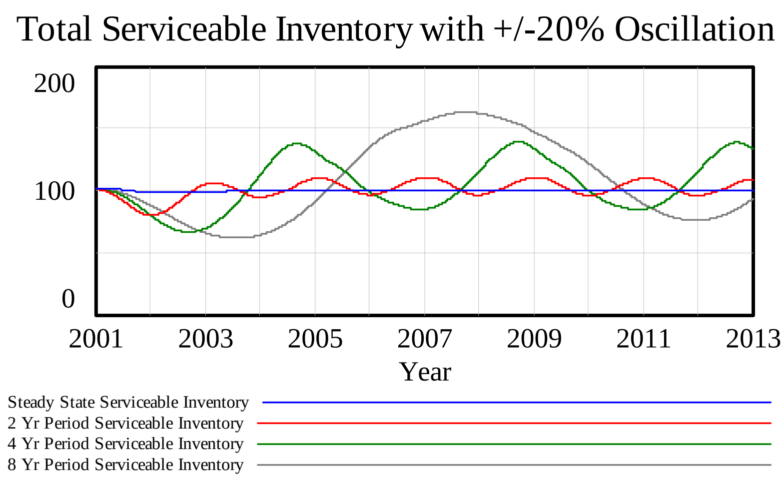

Figure 35: Total Serviceable Inventory with a 20% Oscillation in Demand and a 2, 4, and 8-year Period

A series of simulations were conducted to develop a comparison of the extent of the bullwhip effect on inventory levels, both at the prime supplier as well as the 3rd tier raw material supplier. The impacts of two variables were examined: the period of the oscillation in demands and the averaging time used to calculate expected demands to reflect future orders (see Table 1). The bullwhip effect is clearly evident from the degree of the error in inventory on hand between the constant case and the oscillating demand case in the raw material tier. The amount of the error in serviceable inventory levels between these two cases is dependent upon the months of average demand. The government standard of 24 months is most volatile with the longer oscillation periods.

NO PRODUCTION CONSTRAINTS				
20% variance in demand	Months of Avg Demand			
Period	6	12	24	
2	23%	23%	17%	Percent error in Serviceable Inventory between constant case and variable demand
4	53%	43%	40%	
6	52%	48%	52%	
8	42%	48%	57%	
10	37%	47%	57%	
2	100%	100%	79%	Percent error in Raw Material Inventory between constant case and variable demand
4	100%	100%	100%	
6	100%	100%	100%	
8	100%	100%	100%	
10	100%	100%	100%	

Table 1: Results of Sensitivity Analysis Varying the Period of Demand Oscillation and the Months of Averaging Demand

Case 4 examines a problem that is frequently occurs in government supply chains for high-value aviation spare parts. This is an error in assumed Production Lead Time (PLT). In Case 4, demand begins at the constant level of 14 parts per month. In 2003, demand ramps up over six months to 18 parts a month, increasing 1 unit per month in each of the four regions. It is then assumed that demand ramps down to the original level over a two year period beginning in mid-2009. At the beginning of the simulation, the actual and assumed PLT are both equal to 22 months; in 2004, however, the queuing time for the component eight raw material increases by 10 months, from 2 to 12 months. Component Eight is a necessary component for both new production and for the overhaul process. This assumption reflects circumstances that occurred in 2004 as lead times for raw materials increased dramatically. In the Case 4 simulation, the assumed PLT remains at 22 months and RLT at 11 months for a year before these values are adjusted in the requirements determination process to the actual overall values of 32 months and 21 months, respectively. As a result of this error in the calculations for recommended new buys and for overhaul, inventory levels drop for over three years, creating a significant problem within the supply chain process (see Figure 36). Because of the error, the control system is assuming that it will receive deliveries much more rapidly than it will. In other words, the requirements determination is ordering too little too late because of this error. This is reflected in the very slowly growing Prime New Spares Completion Rate in Figure 37. The recommended procurement action is shown in Figure 38. An interesting dynamic occurs here. The Reorder Point begins to rise thus generating orders and a growing Total Net Assets. However, when the PLT error is corrected during 2005, it causes the Reorder Point to increase and effectively reduce the gap between itself and the Total Net Assets. The result is a counter-intuitive reduction in the recommended orders. This is shown in Figure 39. This prolongs the problems with available inventory. Although the recommended repair action reflects the same increase as the production order rate, overhaul is once again limited by the amount of unserviceable inventory on-hand (see Figure 40), and repair actions are much less than the desired maximum repair action.

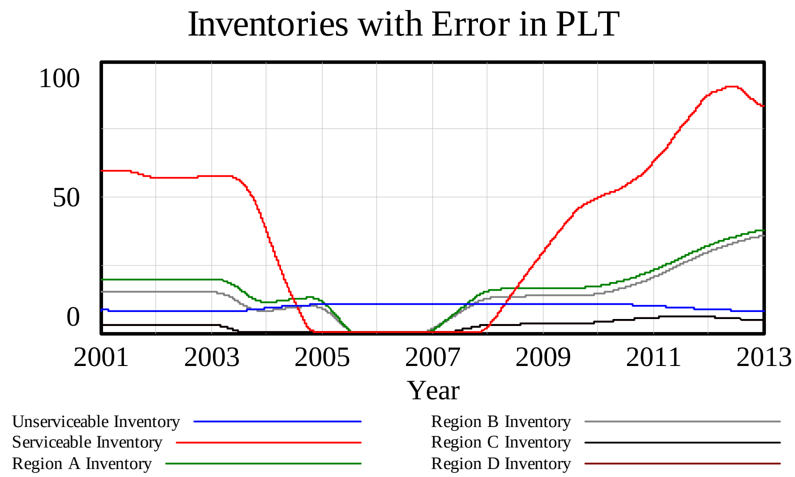

Figure 36: Inventories with a 22-32 Month Discrepancy in Assumed and Actual PLT that Lasts for One Year

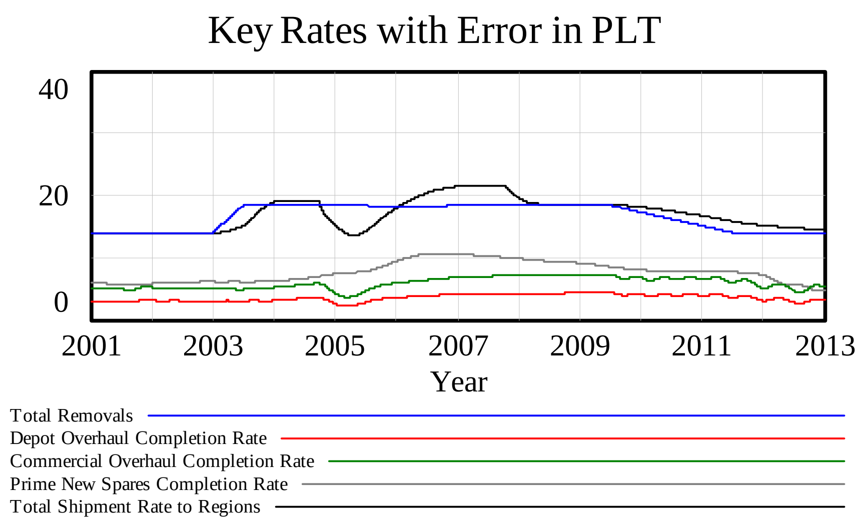

Figure 37: Key Rates with a 22-32 Month Discrepancy in Assumed and Actual PLT that Lasts for One Year

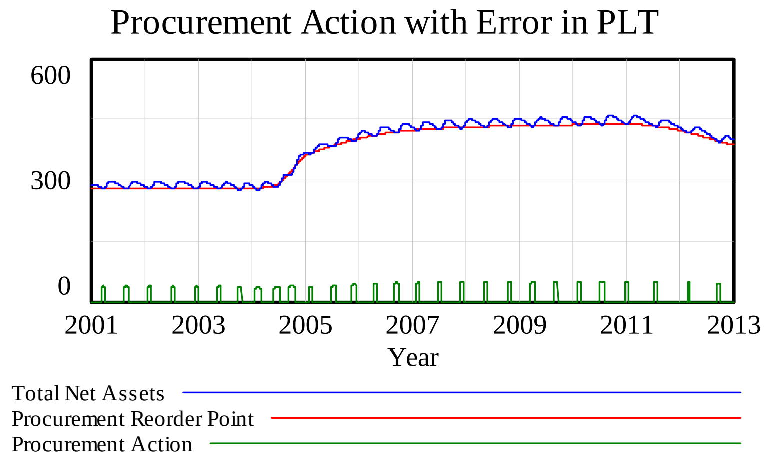

Figure 38: Procurement Action with a 22-32 Month Discrepancy in Assumed and Actual PLT that Lasts for One Year

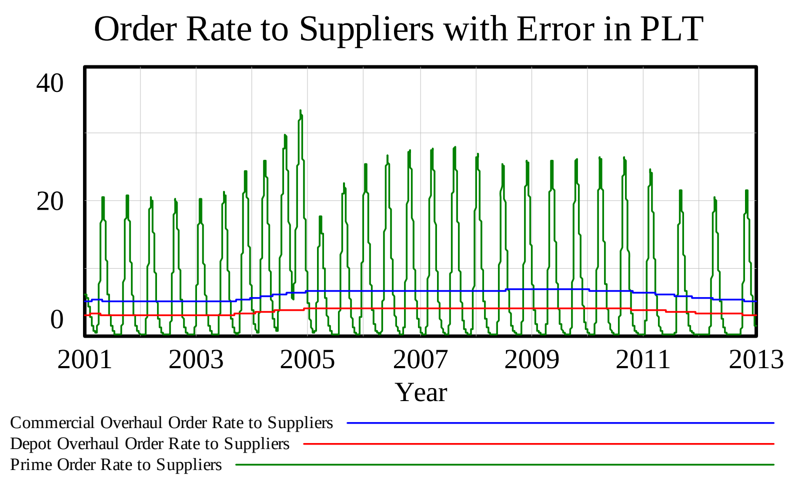

Figure 39: Order Rate of Components for Overhaul and Procurement Processes with a 22-32 Month Discrepancy in Assumed and Actual PLT for One Year

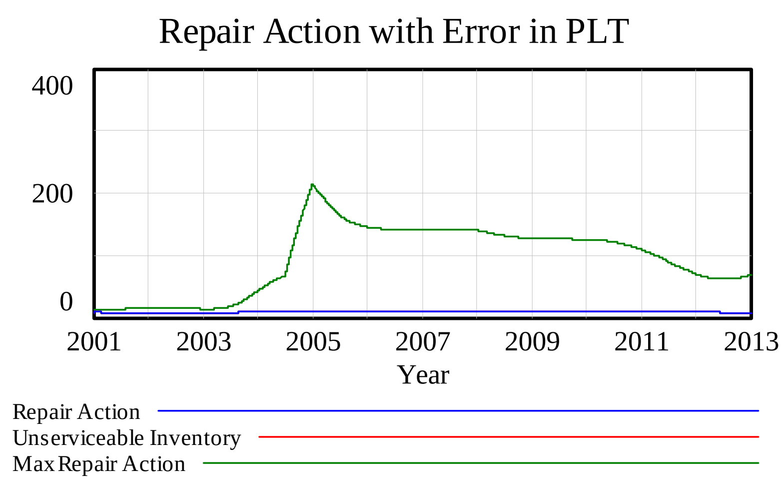

Figure 40: Repair Action with a 22-32 Month Discrepancy in Assumed and Actual PLT that Lasts for One Year

Figures 41 and 42 show the sensitivity of the supply chain to changes in the queuing time for raw material. The affects on serviceable inventory levels are notable. In particular, the last case, in which the PLT increases by 9 months, causes almost a year delay in the start of the recovery of the inventory levels in comparison to the case in which there is no error. Similarly, and to a much greater extent, these delays affect the raw material inventory levels at Tier 2. As may be seen in Figure 42, as would be expected, the greater the PLT and the error, the longer the duration of depleted inventory levels. During this time, backorders are growing at the tier 3 raw material supplier, and inventory levels throughout the supply chain are greatly affected.

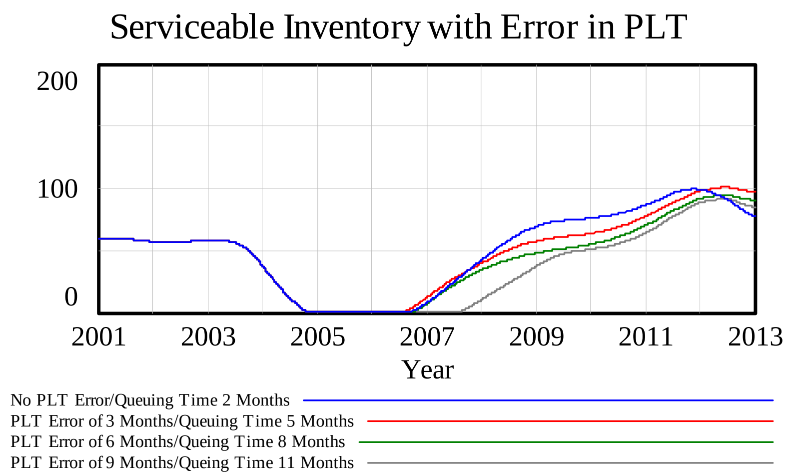

Figure 41: Serviceable Inventory with Varying Errors in PLT Lasting for One Year

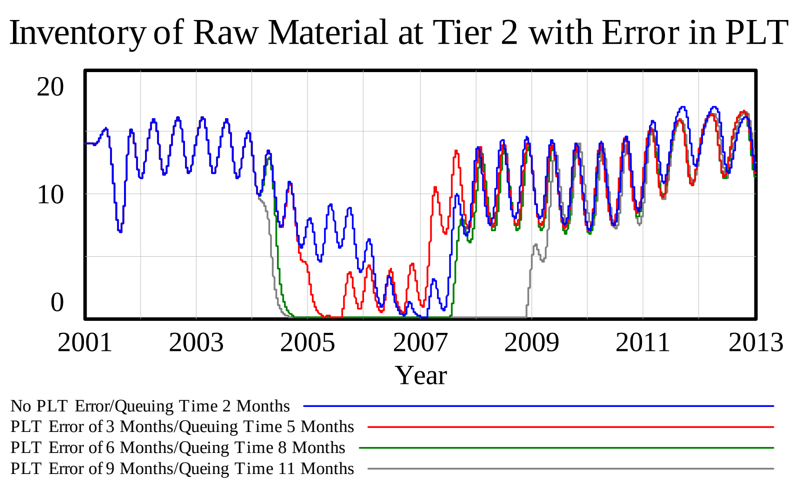

Figure 42: Inventory of Raw Material at Tier 2 with Varying Errors in PLT Lasting for One Year

Case 5 examines another "real world" scenario that occurs frequently and that involves production constraints. Production limitations or constraints are not included in the algorithms of the requirements determination process used by many government agencies. In reality, however, availability of tooling and labor do limit these processes. Case 5 assumes a ramp up in demand in 2003 from 14 to 18 parts a month and a ramp down in demand beginning in 2009 back to 14 parts a month. All other assumptions from Case 1 remain the same, except however, component eight, which is necessary for both overhaul and procurement processes, has a production constraint at the first tier of 20 parts a month. Without this constraint, the first tier supplier of this component should generally be producing up to 22 parts a month after the ramp up in demand. Limiting this production by this small difference delays the start of the recovery of serviceable inventory by about nine months, from late 2006 to mid-2007 (see Figure 43). Additionally, the inventory levels do not fully recover nearly as quickly as the case in which there are no production constraints (see Case 4), and therefore do not reach the level necessary to sustain the higher demand levels before demand ramps back down.

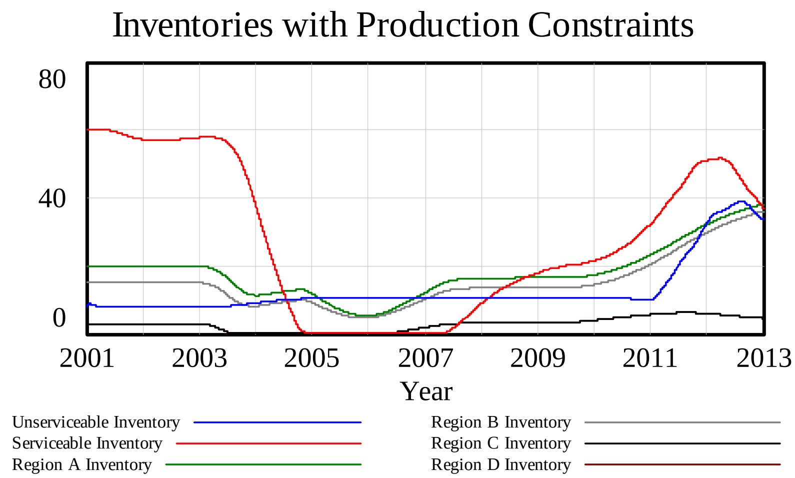

Figure 43: Inventories with a 20/Month Production Limit on Component 8 at Tier 1

Figure 44 presents the results of a sensitivity analysis of the impacts of varying the production limit on component 8 at Tier 1. In the unconstrained case, production is roughly twenty-two units a month. Reducing the limitation to twenty or twenty-one components per month causes a significant impact on the recovery of serviceable inventory. At a limit of 19 components a month, the serviceable inventory levels do not begin to recover for approximately four years after the unconstrained simulation. Both Case 4, incorporating the impacts of inaccurate data, and Case 5, assuming production constraints, demonstrate the high sensitivity of this extended supply chain and the high risk of performance problems. Many government supply chains balance on this knife-edge where small changes can create major problems.

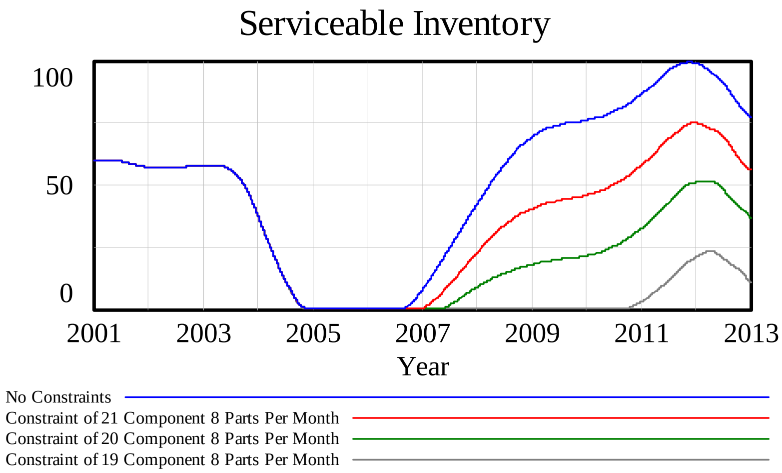

Figure 44: Serviceable Inventory Levels with Varying Production Constraints on Component 8 at Tier 1

Conclusions

Government supply chains for high-value aviation spare parts have experienced considerable problems in assuring stable supply. Many of these problems are shown to be the result of the government requirements determination process, the high sensitivity to inaccurate data and production constraints, and the extended complexity of the multi-tier, multi-channel supply chains. Several key findings have emerged:

(1) The bullwhip effect is strongly evident in the supply chain causing inventory levels to vary greatly throughout all tiers of the supply chain;
(2) Because the ordering process determines recommended procurement and overhaul actions by subtracting two large numbers, the ordering process and the resulting supply chain performance are extremely sensitive to noise and inaccurate data;
(3) Because the requirements determination process does not include the possibility of production constraints, supply chain performance deteriorates rapidly in the face of such constraints.

On-going research activities include using the system dynamics model for the following initiatives:

1. Evaluating alternative, more stable, formulations for the ordering process;
2. Establishing critical push-pull inventories in the multi-tier, multi-channel supply chain to enable more responsive performance by the extended supply chain; and
3. Investigating the impacts of collaborative planning and forecasting and information sharing within the supply chain.

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