The Role of Overhaul in Reducing Lifecycle Costs and Maximizing the Return on Investments to Improve Reliability

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Abstract
Maintaining military aircraft in a high state of readiness requires a non-stop flow of spare parts. These replacement parts can either be new parts from procurement or repaired parts coming from overhaul. The cost of these replacement parts is a major component of total lifecycle operating and sustainment costs. Improvements in reliability can potentially reduce removals and these on-going costs. The overall cost reduction depends upon the interaction over time of any increase in the cost of the new improved part, the increase in reliability, changing demand levels and the role of overhaul. Three overhaul scenarios are examined for cases of improved reliability: (i) old parts improved in overhaul; (ii) old parts not improved in overhaul; and (iii) no overhaul. A system dynamics supply chain model including financial performance metrics is developed to investigate these scenarios through simulation. It is shown that all three scenarios reduce total lifecycle costs and that these reductions can be very significant. The first overhaul scenario is shown to have the greatest returns but the third scenario is only slightly lower. All scenarios are shown to have diminishing investment returns and share a common level of investment that maximizes the percentage reduction in lifecycle costs.
This research was performed at the University of Alabama in Huntsville.

Introduction

Maintaining military aircraft in a high state of readiness requires a non-stop flow of spare parts. Almost every part on an aircraft will be replaced, repaired and ultimately scrapped at some point in time. When parts must be removed, there are two primary sources for the replacement parts: new parts from procurement or repaired parts coming from overhaul. The costs associated with the acquisition, overhaul, transportation and labor to remove and install these parts are a significant part of a system's total Operations & Support (O&S) costs. Moreover, these O&S costs generally account for 70% to 80% of total lifecycle costs, and, as a result, much attention has been directed recently towards the reduction of O&S costs in Defense budgets (GAO-03-57). One important approach for reducing O&S costs is to improve reliability. A part with higher reliability is replaced less often, thus, reducing maintenance labor and the required flow of new and repaired replacement parts. This reduction in the on-going supply of replacement parts potentially, but not necessarily, reduces O&S costs. The overall cost impact depends upon any increase in the cost of the new improved part, the increase in reliability and the demand level. Even if costs are reduced, it may not be a sound business decision depending upon the required investment. Business case analyses must answer the questions: "What are the reductions in lifecycle costs arising from an investment in reliability improvement and what are the return and payback time for the required investment?"

Previous efforts (Forbes, McQueary) have investigated the likely payoffs in improved reliability arising from investments to improve reliability. This research established a log-log linear relationship between the percent improvement in reliability and the ratio of the investment to the part cost. Killingsworth, Speciale and Martin have taken a next step by estimating the cost reductions arising from the improved reliability and the returns on investment. That research demonstrated that the returns generated by investments to improve reliability for aviation parts depended upon the cost of the part, the flight hours per month, and the investment level. Importantly, this prior research assumed that in the overhaul process, the removed parts could be transformed into the new design with improved reliability. This transformation, however, may not always be possible. There are three basic feasible scenarios regarding the old parts and overhaul:

1. Older parts can be transformed during the overhaul process into the new design with improved reliability. Thus, both the new parts coming from acquisition and the parts coming from overhaul now both possess the improved reliability. This was the assumption in the prior research.
2. The older parts cannot be transformed into the new parts but there is either insufficient production capacity or funding to provide for all new parts. As a result, the old parts go through overhaul and are re-issued but with the old level of reliability.
3. The older parts cannot be transformed into the new parts but there is sufficient funding and production capacity for new parts to make up for the lost overhaul source. In this case, all old parts are scrapped. As a result, all parts being issued are new and possess higher reliability.

The objective of this research is to investigate the impacts of these three alternative overhaul scenarios on the returns generated by investments in reliability improvements. As noted, many factors affect the potential return: the cost of the new part, cost of the overhaul, operating hours, improvement in reliability, increase in cost arising from the improvement, and the investment being made. Moreover, since most aviation system life spans can exceed two decades, the analysis must address the dynamics of the supply system over an extended time period. The analysis must capture the interplay of the many factors over time.

Analytical Approach

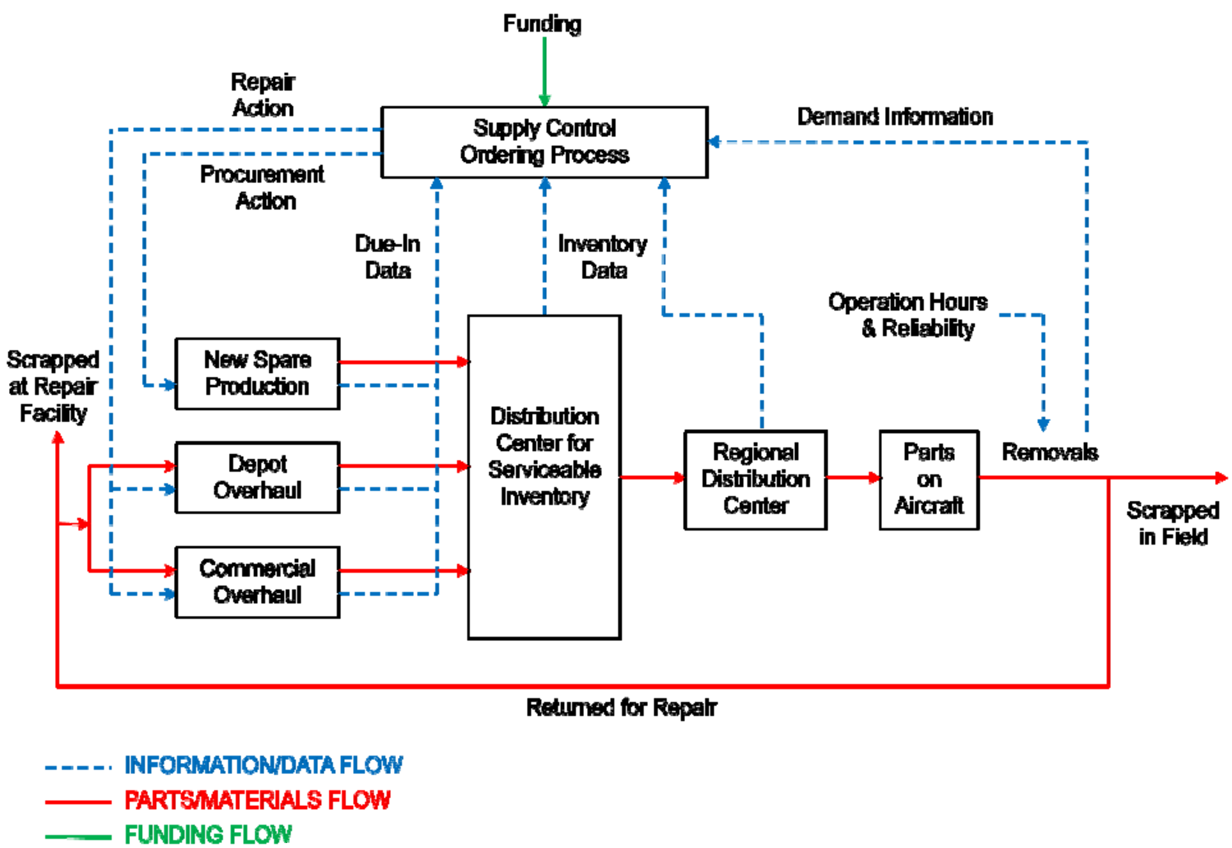
System Dynamics is a well-suited tool for understanding the structure and dynamics of complex supply chain systems. From its very beginning, System Dynamics has been used to analyze supply chains as a modeling and simulation tool for policy analysis. Forrester's (1958) groundbreaking article in the Harvard 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's model included factory, distribution, and retail tiers in the supply chain, but no suppliers to the factories. In 2000, John Sterman expanded on Forrester's supply chain models, including multiple-tiered suppliers linked to the factories. Huang and Wang (2007) explored the bullwhip effects in a closed loop supply chain system. Simchi-Levi (2008) and Lee (1997) addressed the bullwhip effects from an analytical perspective on complex supply chains. Schroeter and Spengler (2005) addressed the strategic management of spare parts in closed loop supply chains. Angerhofer and Angelides (2000) presented an in-depth discussion of system dynamics modeling in supply chain management. Killingsworth, Chavez, and Martin (2008) analyzed the government ordering process within a system dynamics in two forms: including the extended supply chain and excluding the extended supply chain. Also, Killingsworth, Speciale, and Martin (2009) expanded on the DoD supply chain with the impacts of improved reliability of total lifecycle costs.

The intent of the current research is to analyze the importance of overhaul (maintenance and repair) over the life span of an aviation system. Incorporating overhaul, total lifecycle costs, and improvements in reliability within a supply chain, a system dynamics model can capture both the multitude of variables and the dynamics of time. By using appropriate discount and inflation rates, cumulative and annual costs are measured in relation to investment amounts to weigh the overall benefits for reliability improvement and total overhaul costs within the government supply chain. By modeling the three specific overhaul scenarios for aviation parts in the supply chain over the system's life span, total costs (both constant and current dollars), benefit investment ratios, and payback periods can be determined for comparison.

Model Description

An overview of the supply chain for high-value aviation parts is shown in Figure 1. This diagram illustrates the flow of parts from new production and overhaul to the final customer. Also shown is the reverse logistics path in which removed parts may be returned to the overhaul facility for repair. The overall supply chain process is managed in a feedback form by the government's ordering or requirements determination process. (Killingsworth, Chavez, Martin, 2008) These algorithms are typically embedded in a computerized process utilized by item managers, such as the Army's Supply Control Study. Based upon the calculated recommendations, repair action or procurement action will be initiated. This process, or something similar, is used by most government and defense supply chains for high-value parts. (Rosenman, 1964)

FIGURE 1: Overview of Supply Chain Model



By monitoring levels of inventory, due-ins, due-outs, and historical demand levels, the ordering process determines the recommended number of buys and repairs. The supply of parts comes from three possible sources: production of new items, commercial overhaul of worn or damaged parts, and government overhaul of worn or damaged parts. Once the production or overhaul process is completed, parts are transferred to a central distribution inventory. Geographical regions have an inventory of key spare parts, and these inventories are replenished from the central distribution inventory. The demand for a part is driven by the total number of installed parts, the monthly operating hours, and the failure rate per part per operating hour, sometimes expressed as a mean time between failure (MTBF). Removed parts that are excessively damaged and deemed unfit for repair may be scrapped in the field and not returned. Most high-dollar parts, however, are returned to a maintenance depot for evaluation. Those parts not scrapped upon evaluation will then be sent either to a government or commercial overhaul facility. Parts coming from both new production and overhaul are delivered to the central inventory and are then available for shipment to the regional inventory centers.

The primary external drivers for the Financial and Supply Chain Model are listed in Figure 2.

Figure 2: Primary Demand Drivers for Supply Chain and Financial Model

Mean Time Between Failure (MTBF)
Monthly Flying Hours
Number of Aircraft

The mean time between failures is an engineering measure that specifies the amount of time (measured in hours) the part can be in operation before it is expected to fail. For this model, the initially assumed MBTF is 1,390 hours. This number is increased to examine those cases with improved reliability. The monthly flying hours specifies the hours the aircraft and associated part are assumed to operate per month. For this analysis, fourteen (14) flying hours per month are assumed. The number of aircraft in this case is 463 and there are three installed parts of interest on each aircraft. There are thus 19,446 total monthly operating hours for the part of interest (14 flight hours per month)(463 aircraft)(3 installed parts per aircraft). With 1,390 hours between failures, the total average failures per month are fourteen. This is the basic demand level and the number of removals each month.

The key assumed parameters within the model are presented in Figure 3.

Figure 3: Important Parameters for Supply Chain and Financial Model

Administrative Lead Time (ALT)	Inflation Rate
Repair Lead Time (RLT)	Discount Rate
Production Lead Time (PLT)	Scrap Rate in Field
Cost of New Part	Scrap Rate at Depot
Cost of Overhauled Part	

Before the production/repair process begins, contracts must be approved at various levels within the government; this elapsed time is known as administrative lead time (ALT), and typically ranges from a few weeks to six months. For this model, ALT is assumed to be one month. After contracts are in place, the repair or production process begins. The elapsed time between the contract(s) approval and part delivery to the government is called either the repair lead time (RLT) or production lead time (PLT). For this model, an 11-month RLT and 22-month PLT are assumed. The cost of a new part and cost of an overhauled part are the cost of a new part through procurement and the cost of a part repaired through overhaul, respectively. For this model it is assumed the cost of a new part is $250,000 and $187,500 for a repaired part. The inflation rate allows for forecasted growth in the price of all future expenditures. This model assumes a 6% inflation rate. The discount rate allows for analysis of a present value of expected costs within the simulation. Simply, this measure calculates the present value of total costs to be incurred in the future. A discount rate of 4% is used in this model. The scrap rate in the field is the percentage of parts scrapped in the field and deemed unserviceable and incapable of repair. For Scenarios 1 and 2, the scrap rate in the field is 15%. For Scenario 3, the scrap rate in the field is 100%, meaning no parts are returned to the depot for evaluation. The scrap rate at the depot is the percentage of parts that are scrapped at the depot facility following evaluation. For Scenarios 1 and 2, this percentage is 35%. As noted, in Scenario 3, no parts are returned for evaluation at the depot.

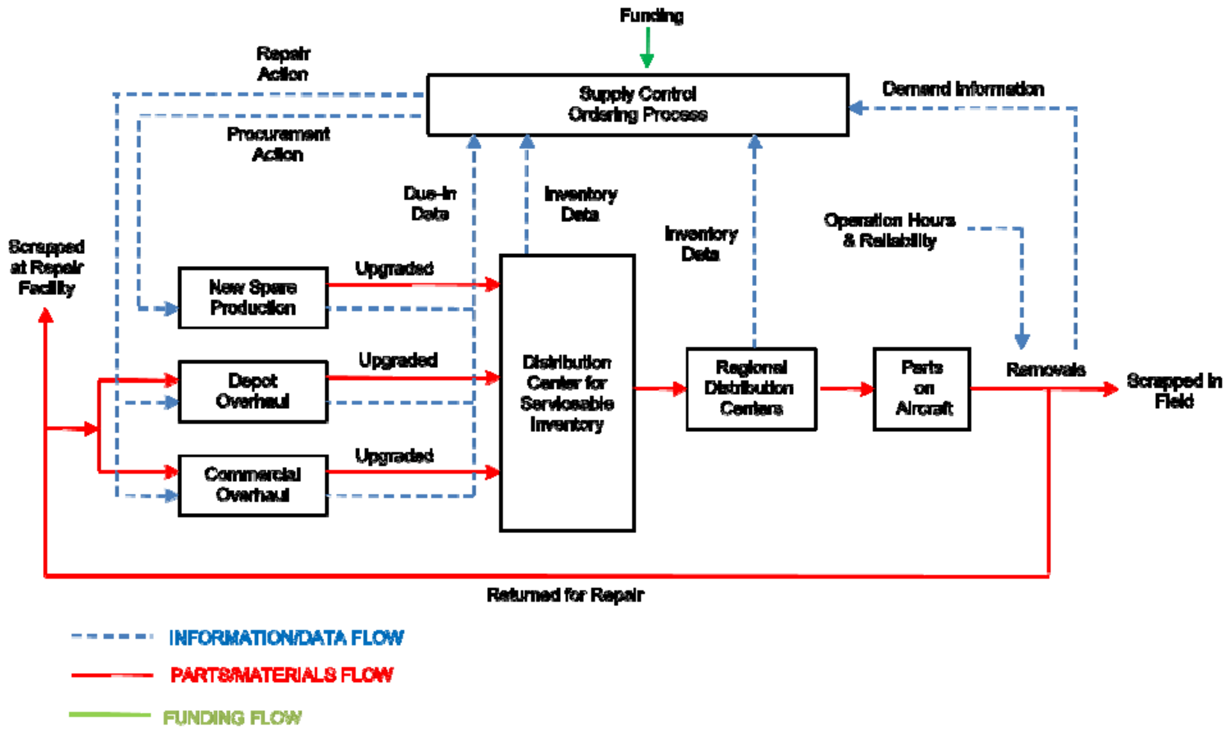
The intent of this research is to determine how investments made in the supply chain for improved reliability reduce total lifecycle costs under alternative overhaul scenarios. It is assumed in the model that the investment occurs over a three year period that includes design, manufacturing, test, and certification. Shorter or longer investment are easily included and examined in the model structure.

The investment in reliability impacts the spending amounts for each year after the new improved part is introduced, depending on the degree of reliability improvement for the part and any changes in the unit cost of the part. It may very well be the case that the improved part will have a higher production cost and the model enables the investigation of tradeoff between improved reliability, higher unit cost, and reduced demand.

The three overhaul scenarios are described in greater detail below:

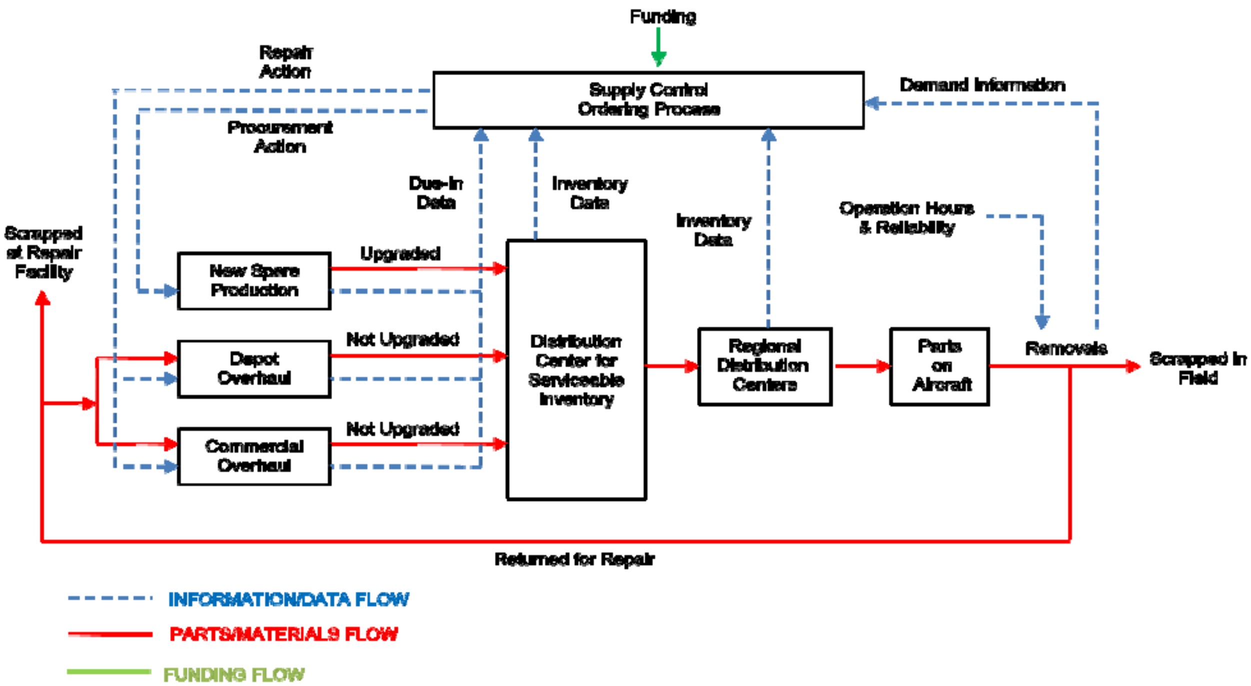
1. In this first scenario, the older parts that are removed are transformed during the overhaul process into the new design with improved reliability. Thus, new parts coming from acquisition and also parts coming from overhaul now both possess the improved reliability. This was the assumption in the prior research effort. For this scenario, the scrap rate in the field is 15% and the scrap rate at the depot facility is 35%. Figure 4 shows an overview of the model structure for this scenario.

Figure 4: Overview of Model Structure for Scenario 1
Reliability of Older Parts Upgraded During the Overhaul Process



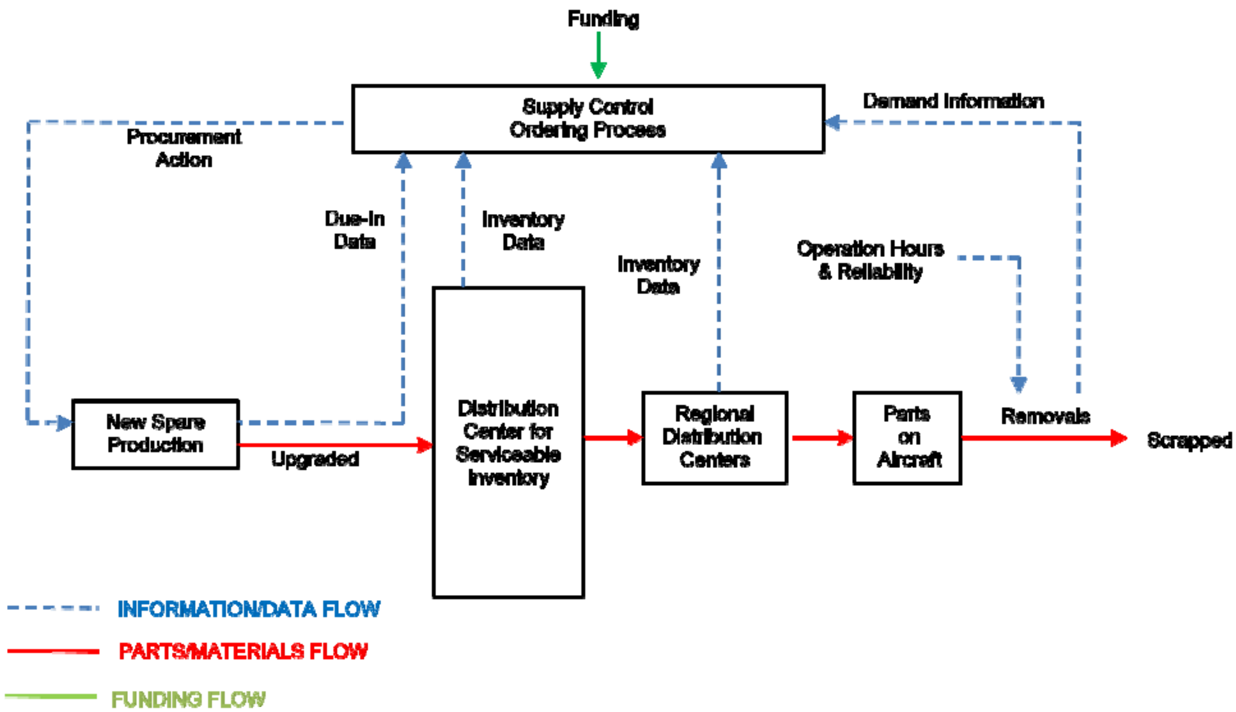
2. In the second scenario, the older parts that are removed from the aircraft cannot be transformed in overhaul to the new design with higher reliability. These older design parts undergo overhaul but are returned to the supply system with the prior reliability levels. Thus the population is a renewing mix of new and old designs. The newly procured parts operate at the new and improved reliability levels, but the old, refurbished parts will remain in operation at original reliability levels. In this case, it takes much longer to reach overall improved reliability levels and reduced demands. For this scenario the scrap rate in the 15% and the scrap rate at the depot facility is 35%. Prior research has not examined this scenario.

Figure 5: Overview of Model Structure for Scenario 2
Reliability of Older Parts Not Upgraded During the Overhaul Process



3. In this scenario, the older parts cannot be transformed into the new improved reliability part. This is similar to the assumption in Scenario 2. It is assumed, however, in this scenario that there is sufficient funding and production capacity for an increase in the production rate of new parts to make up for the overhaul. In this case, all old parts are scrapped. A key assumption for this case is that the supply chain has the capacity and resources to manufacture the new parts fast enough to fill all orders and overcome the lack of overhaul supply. For this scenario the scrap rate in the field is 100%, as all parts removed from the aircraft will be replaced with only newly procured parts. Figure 6 presents the model overview for this case in which there is no reverse logistics of old parts following the introduction of the new part. Prior research has not examined this scenario.

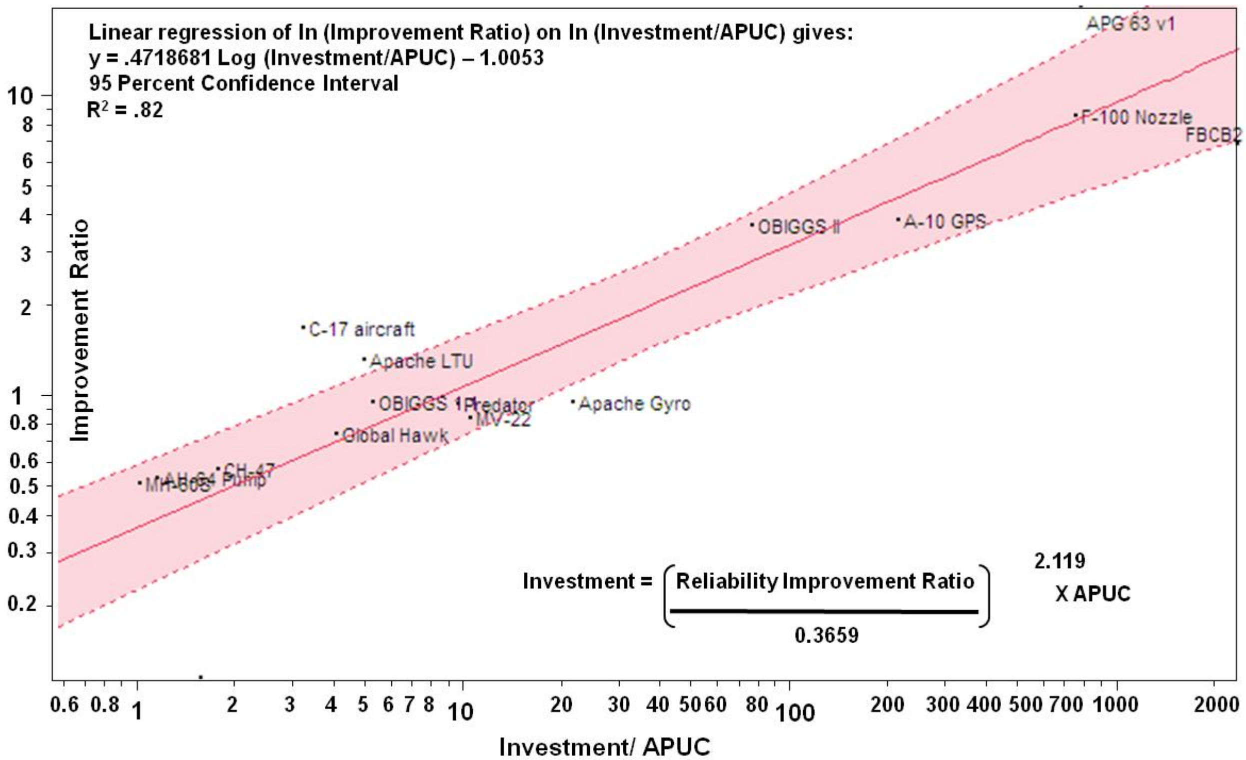
Figure 6: Overview of Model Structure for Scenario 3
Only New Parts are Issued, No Overhaul Process
After Introduction of Improved, More Reliable New Part



Financial Analysis and Supply Chain Behavior

Because of the strong tie between reliability and sustainment costs, the DoD Director of Operational Test and Evaluation sponsored research to investigate the empirical relationships between reliability investments, improvements in reliability and life-cycle support costs. In this research, a preliminary relationship between investment in reliability (normalized by average production unit cost) and achieved reliability improvement was developed. This relationship is presented in Figure 7 and is taken from a presentation delivered by Mr. Charles E. McQueary, Director, Operational Test and Evaluation, Office of the Secretary of Defense.

Figure 7: Empirical Relationship Between Reliability Improvements & Reliability Investments



***Source*: Life Cycle Cost Savings by Improving Reliability, Dr. Charles E. McQueary**
Director, Operational Test and Evaluation, January 15, 2009
www.gw-itea.org/.../**McQueary**GW-ITEAluncheonPresentationJan2009.ppt

As an illustrative data point on the graph of Figure 7, the research determined that the Predator program invested a total cumulative amount of $39.1 million in reliability investments over a nine year period. The ratio of this investment to the Average Production Unit Cost (APUC) of $4.2 million is 9.3 and is the value of the x axis for the Predator data point. The research also determined that the overall failure rate of the Predator was reduced by 48.1 percent, resulting in an overall improvement in MTBF from 40 hours in FY98 to 77 hours in FY06, or a 92.5 percent improvement in reliability. This is the y-axis point for the Predator. The other data points on this graph reflect the results of similar analysis.

For the analysis presented in this research, cases are evaluated for Investment/APUC ratios of 20 (Case 1), 30 (Case 2), and 40 (Case 3). For a part costing $250,000, these cases require investments of $5, $7.5 and $10 million. Correspondingly, these scenarios had reliability improvement ratios of 1.5, 2.0, and 2.25, respectively. The improvement ratios of 1.5 (150%), 2.0 (200%), and 2.25 (225%) may be viewed as generating percent reductions in failure rate per flight hour of 60% (Case 1), 66.7% (Case 2), and 69.2% (Case 3). These three cases are used in analysis of the three overhaul scenarios.

For each scenario, a base case projection is compared to several alternative cases that include reductions in failure rate per flight hour of 60.0%, 66.7%, and 69.2%. Each case has an associated investment amount for its specific improvement in reliability. Annual spending is used to determine the payback ratio in years (break-even) and the total benefit for the predetermined investment amount. Additionally for each case, the total annual costs and benefit per defined investment are determined. These results indicate those investment amounts that are most appropriate for achieving the greatest cost savings and total benefit.

Overhaul Scenario 1: Old Parts Undergo Overhaul, are Upgraded in Overhaul and are Re-Issued with New Improved Level of Reliability

For Scenario 1, overhauled parts are capable of being upgraded to the new level of improved reliability. Once the improved part becomes available at the beginning of year four, all parts being issued have improved reliability. For this scenario, three cases of improved reliability are examined. Figures 8, 9, 10 and 11 present the simulation results for the case with the greatest reliability improvement, a 69.2% reduction in failures per flight hour. Figure 8 presents the recurring monthly demands for this case. With constant flight hours, demand is constant at fourteen per month until the new parts begin to be introduced. Each time an older part is removed, a part with improved reliability is installed, and, as a result, the overall average meantime between failures begins to decline reflecting the mix of new and old parts. After approximately eight years, all of the parts are the improved parts with higher reliabillity and demand has dropped to a new steady level. Since parts are lasting longer, fewer parts are demanded. Figure 9 illustrates that when the total net assets drop below the procurement reorder point, a procurement action is initiated ordering new parts. The total net assets are calculated by summing the available wholesale inventories, the items due in from procurement and repair processes, and subtracting the number of items due out. As may be seen in Figure 9, there is an eight year period where total net assests exceed the reorder point. This creates an eight year period where no parts are ordered through new procuremen. This period of time with no new orders can be explained by reviewing the graph of inventories presented in Figure 11. The growth in inventories is largely the result of long time lags in the system. First, forecast demands used to calculate the reorder point are often based upon a two year rolling average of demand. Thus, as the improved parts begin to reduce demand, that reduction is only slowly taken into account in the rolling average and the forecast. Secondly, the production lead time is two years so a significant pipeline of production work in progress exists. This pipeline empties into the supply system at the same time that demand is falling and, as a result, inventories increase. With the growth in inventories, new production is essentially halted for several years and only repaired parts are needed to sustain operations. Figure 10 illustrates the completion rates for overaul and new procurement. Both completion rates decline once the reliability improved parts are introduced. The halt in new production is not a good thing and, in fact, could be quite troublesome. The industrial base for many defense aviation parts is quite small and this type of gap could well lead to a loss of suppliers. Integrated planning and careful forecasting of inventories could prevent the excess supply and the cutback in orders.

Figure 8: Recurring Demands for Scenario 1

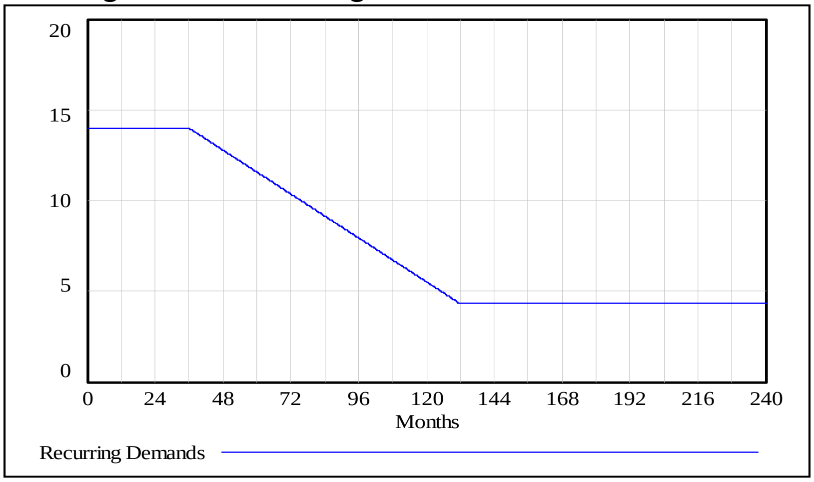


Figure 9: Procurement Action for Scenario 1

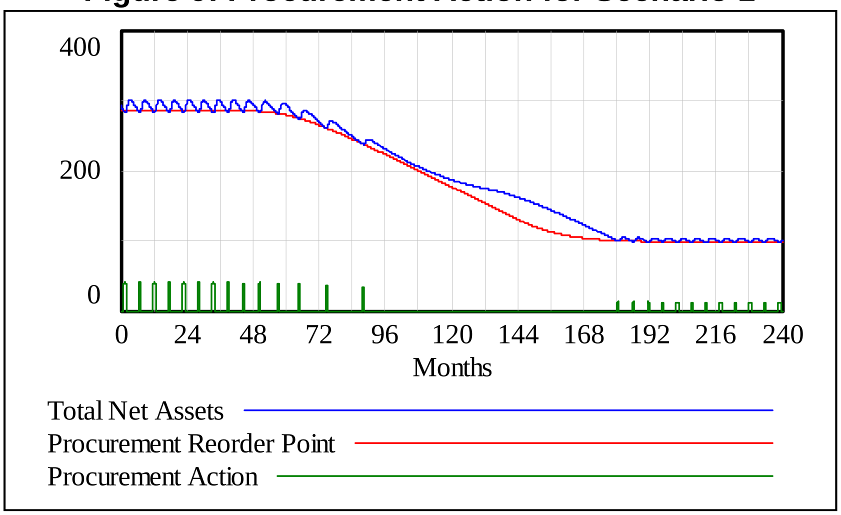


Figure 10: Overhaul and New Procurement Production Completion Rates

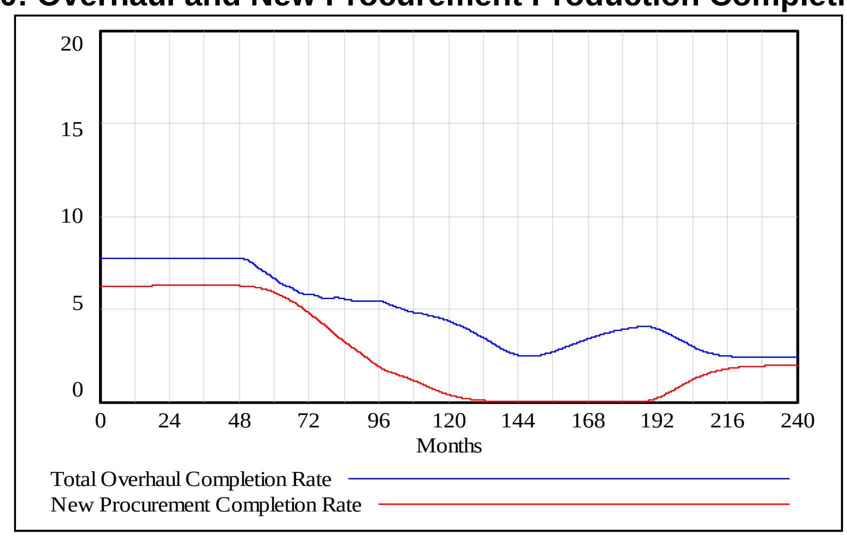


Figure 11: Inventories for Scenario 1

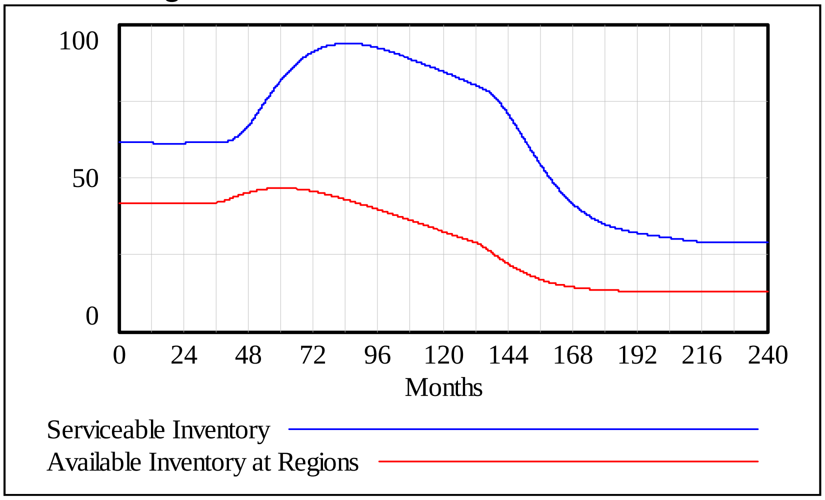


Figure 12 presents the financial results for Scenario 1. This chart presents the current dollar annual expenditures for the base case and three cases with improved reliability. Note that the spend column for each case includes the investment being made over the first three years in which the new part is developed. Thus, for Case 1, the negative savings (expressed in current dollars) of $1.6, $1.8, and $1.8 million are equal to the initial investment amount of $5 million. Once the improved part is introduced at the beginning of year four, positive annual savings begin to accrue. For Cases 1, 2, and 3, the cumulative lifetime savings are $655.6 million, $725.7 million and $752.0 million respectively. It is important to note that these large savings are arising from an investment in reliability for a single part with a monthly demand of fourteen (14) and a cost of $250,000 per unit. This indicates the very large potential in lifecycle savings that are possible from improved reliability. All of the breakeven payback points are between 3 and 3.4 years, a fairly rapid payoff for the investments. However, as may be seen in the lower section of Figure 12, the ratio of benefits to investment has a much broader range going from 131 for Case 1 to 97 for Case 2 and dropping to 75 for case 3 with the highest investment of $10 million. This clearly indicates the very real potential for diminishing returns on higher levels of investment.

It is important to note that in the three cases of improved reliability discussed above, the cost of the improved part with higher reliability remains at $250,000. Killingsworth, Speciale and Martin (2010) have examined the impacts on the financial benefits of increases in part cost due to the new design. This analysis showed that such a cost increase would reduce the savings and the benefit to investment ration, but under reasonable assumptions for cost increase, the financial benefits remained very attractive.

FIGURE 12: Financial Results for Scenario 1 – Cases Base, 1, 2, and 3

Current Dollars Annual Spending Amounts
($Millions)*

	Percent Reduction in Failure Rate Per Flight Hour						
Year	Base Spend 0%	Case 1 Spend 60%	Case 1 Savings	Case 2 Spend 66.7%	Case 2 Savings	Case 3 Spend 69.2%	Case 3 Savings
1	$36.2	$37.8	-$1.6	$38.7	-$2.5	$39.5	-$3.3
2	$38.3	$40.1	-$1.8	$41.0	-$2.7	$41.9	-$3.6
3	$40.9	$42.7	-$1.8	$43.7	-$2.8	$44.6	-$3.7
4	$43.4	$43.4	$0.0	$43.4	$0.0	$43.4	$0.0
5	$46.0	$45.9	$0.1	$45.9	$0.1	$45.9	$0.1
6	$48.8	$44.7	$4.1	$44.1	$4.7	$43.9	$4.9
7	$51.8	$40.5	$11.3	$39.2	$12.6	$38.7	$13.1
8	$55.1	$36.1	$19.0	$34.1	$21.0	$33.4	$21.7
9	$58.5	$32.5	$26.0	$28.2	$30.3	$28.7	$29.8
10	$62.1	$29.1	$33.0	$25.4	$36.7	$24.2	$37.9
11	$65.9	$25.9	$40.0	$21.1	$44.8	$19.9	$46.0
12	$70.0	$22.2	$47.8	$17.0	$53.0	$15.4	$54.6
13	$74.3	$18.8	$55.5	$13.6	$60.7	$11.6	$62.7
14	$78.9	$20.7	$58.2	$15.3	$63.6	$13.3	$65.6
15	$83.8	$26.3	$57.5	$19.7	$64.1	$17.7	$66.1
16	$89.0	$32.0	$57.0	$24.3	$64.7	$21.6	$67.4
17	$94.5	$36.3	$58.2	$29.2	$65.3	$25.2	$69.3
18	$100.3	$39.3	$61.0	$32.5	$67.8	$29.2	$71.1
19	$106.5	$42.4	$64.1	$35.3	$71.2	$32.3	$74.2
20	$113.1	$45.1	$68.0	$40.0	$73.1	$35.0	$78.1
Cumulative	$1,357.4	$701.8	$655.6	$631.7	$725.7	$605.4	$752.0

Investment Over Three Year Period (Years 1 - 3)**

		Case 1	Case 2	Case 3
Case 1 $5 Million	Break-Even (Years)	3.08		
Case 2 $7.5 Million	Break-Even (Years)		3.21	
Case 3 $10 Million	Break-Even (Years)			3.38

Ratio of Benefits to Investment***

	Case 1	Case 2	Case 3
Case 1 $5 Million	131.0		
Case 2 $7.5 Million		96.8	
Case 3 $10 Million			75.2

*Annual spending amounts include investment spending during first three years
**Breakeven period is the time required to recapture the investment through savings after the investment period
***Benefits are the total cumulative savings

Overhaul Scenario 2: Old Parts Undergo Overhaul But Are Not Upgraded in Overhaul and Are Re-Issued with Old Reliability

For Scenario 2, it is assumed that the overhaul process cannot upgrade older parts to perform at the same reliability levels as the new parts. It is assumed, moreover, that there is neither the funding nor production capacity to do away with overhaul and only supply new parts. As a consequence, at the beginning of year four, new parts with improved reliability are being introduced into the system along with older parts coming from overhaul that have the historical reliability level. Figures 13, 14, 15, and 16 present the simulation results for this overhaul scenario. Figure 13 illustrates the level of recurring demands over time. Significantly different from Scenario 1, the level of recurring demands requires over sixteen years to reach the new lower level. This is because in Scenario 1, all parts used for replacements had the new higher level of reliability. In contrast, in Scenario 2, many of the parts being used have the older level of reliability. It thus takes longer for the changeover in the population. Figure 14 presents the procurement actions over time. As the new parts are introduced, the time between orders lengthens and the order size becomes somewhat smaller. Similar to Scenario 1, a lower total level of net assets is required over time, as more newly improved parts enter the supply chain and demand drops. Figure 15 illustrates the total overhaul and new procurement completion rates. For this scenario, both completion rates decline correspondingly once the new parts are introduced. Lastly Figure 16 shows that inventory levels increase upon the introduction of the reliability improved parts, and then decline for the remainder of the simulation. Importantly for this case, with demand falling much more slowly, the inventories do not grow to the same extent as in Scenario 1 and there is no period without orders for new parts as was seen in Scenario 1. This is a positive development for the stability of the supplier base.

Figure 17 presents the financial results for Scenario 2 including the base case and reliability improvement cases 1, 2 and 3. Note that the reliability improvements and the investments are the same as in Scenario 1 yet total cumulative savings are much lower, the payback years are higher, and the benefit to investment ratio is lower for all three cases compared to Scenario 1. Recall that in Scenario 1, all older parts were upgraded to the higher reliability design during the overhaul process. This means that starting in year four of Scenario 1, all parts being supplied have higher reliability and demand drops fairly quickly over a period of eight years. In contrast, in Scenario 2, the older parts cannot be upgraded and after overhaul are returned to service with the lower reliability. As a result, turnover of parts occurs more slowly and demand does not drop quickly, requiring approximately sixteen years to reach the new lower level. As a result, savings do not accrue so rapidly, and this scenario has lower financial returns and is not as attractive as Scenario 1.

Figure 13: Recurring Demands for Scenario 2

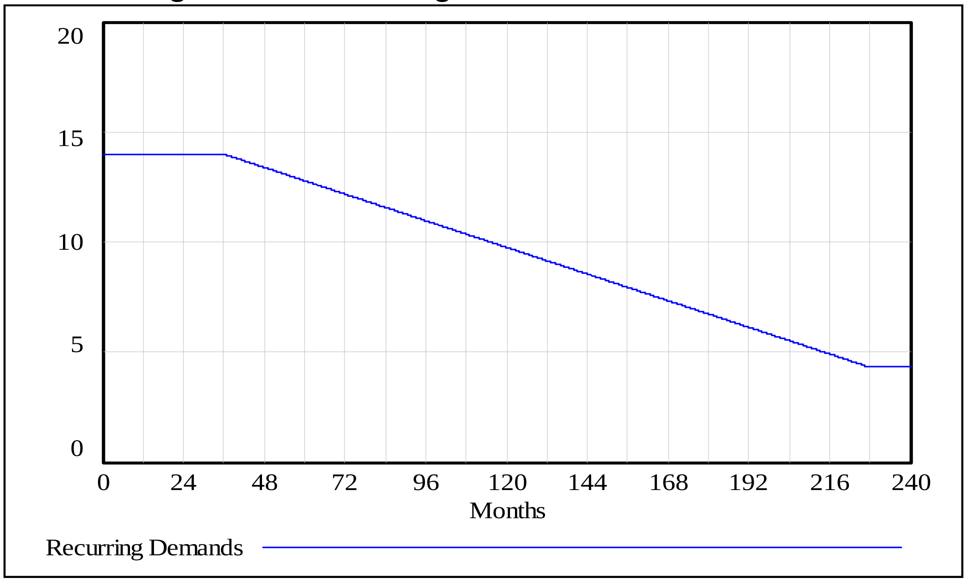


Figure 14: Procurement Action for Scenario 2

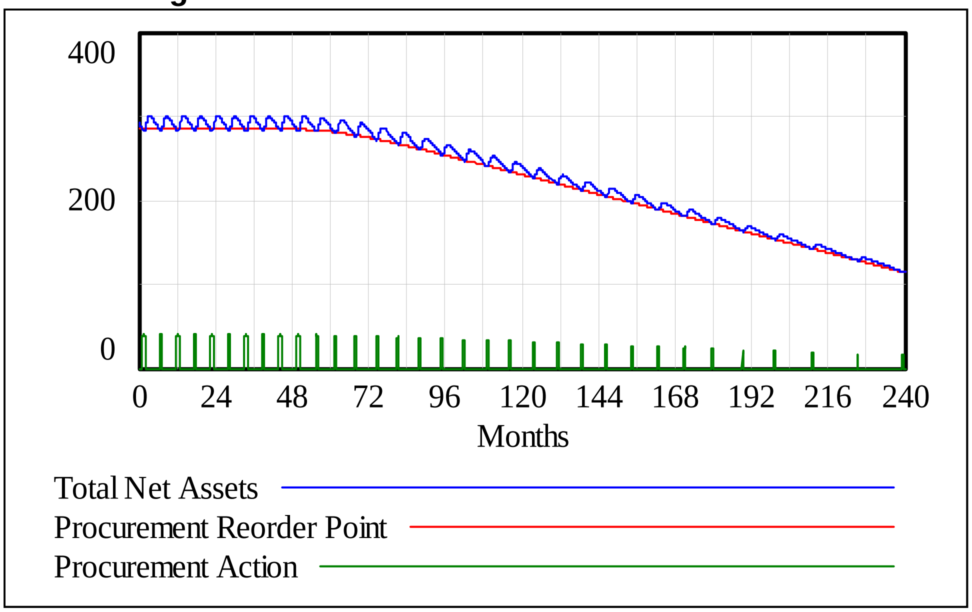


Figure 15: Overhaul and New Procurement Production Completion Rates

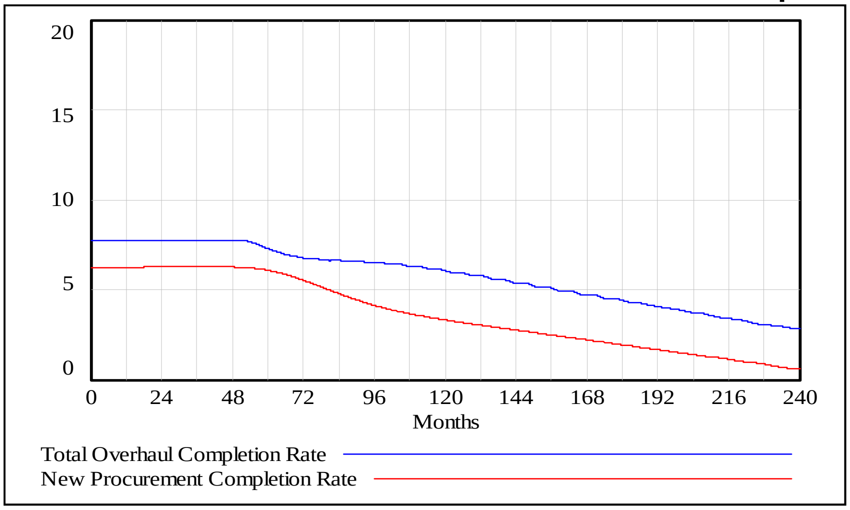


Figure 16: Inventories for Scenario 2

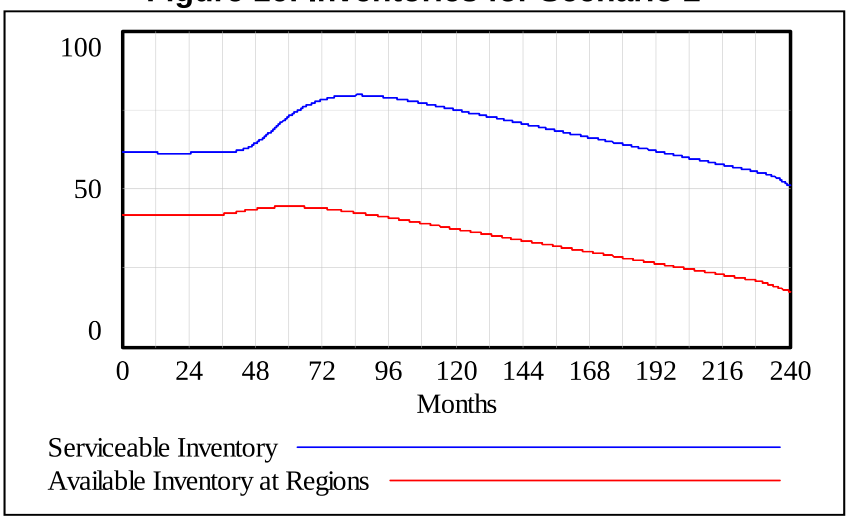


FIGURE 17: Financial Results for Scenario 2 – Cases Base, 1, 2, and 3

Current Dollars Annual Spending Amounts ($Millions)*

	Percent Reduction in Failure Rate Per Flight Hour						
Year	Base Spend 0%	Case 1 Spend 60%	Case 1 Savings	Case 2 Spend 66.7%	Case 2 Savings	Case 3 Spend 69.2%	Case 3 Savings
1	$36.2	$37.8	-$1.6	$38.7	-$2.5	$39.5	-$3.3
2	$38.3	$40.1	-$1.8	$41.0	-$2.7	$41.9	-$3.6
3	$40.9	$42.7	-$1.8	$43.7	-$2.8	$44.6	-$3.7
4	$43.4	$43.4	$0.0	$43.4	$0.0	$43.4	$0.0
5	$46.0	$46.0	$0.0	$46.0	$0.0	$46.0	$0.0
6	$48.8	$47.0	$1.8	$46.7	$2.1	$46.6	$2.2
7	$51.8	$46.2	$5.6	$45.6	$6.2	$45.3	$6.5
8	$55.1	$45.7	$9.4	$44.7	$10.4	$44.3	$10.8
9	$58.5	$45.6	$12.9	$44.1	$14.4	$43.5	$15.0
10	$62.1	$45.7	$16.4	$43.7	$18.4	$43.0	$19.1
11	$65.9	$45.8	$20.1	$43.6	$22.3	$42.9	$23.0
12	$70.0	$46.0	$24.0	$43.6	$26.4	$42.6	$27.4
13	$74.3	$46.3	$28.0	$42.9	$31.4	$41.6	$32.7
14	$78.9	$46.1	$32.8	$42.3	$36.6	$41.2	$37.7
15	$83.8	$45.6	$38.2	$41.7	$42.1	$39.8	$44.0
16	$89.0	$45.4	$43.6	$40.1	$48.9	$38.6	$50.4
17	$94.5	$44.5	$50.0	$39.1	$55.4	$36.8	$57.7
18	$100.3	$43.3	$57.0	$37.2	$63.1	$34.6	$65.7
19	$106.5	$42.3	$64.2	$34.9	$71.6	$32.3	$74.2
20	$113.1	$40.5	$72.6	$32.5	$80.6	$29.4	$83.7
Cumulative	$1,357.4	$886.0	$471.4	$835.5	$521.9	$817.9	$539.5

Investment Over Three Year Period (Years 1 - 3)**				
Case 1 $5 Million	Break-Even (Years)	3.57		
Case 2 $7.5 Million	Break-Even (Years)		3.87	
Case 3 $10 Million	Break-Even (Years)			4.12

Ration of Benefit to Investment ***			
Case 1 $5 Million	94.3		
Case 2 $7.5 Million		69.6	
Case 3 $10 Million			54.0

*Annual spending amounts include investment spending during first three years
**Breakeven period is the time required to recapture the investment through savings after the investment period
***Benefits are the total cumulative savings

Overhaul Scenario 3: All Old Parts are Scrapped and Do Not Undergo Overhaul, New Production Ramps up to Overcome Loss of Overhaul Supply Stream

In Scenario 3, it is assumed that all of the removed parts with the old design are scrapped and do not undergo overhaul. A highly important assumption for this scenario is that funding and production capacity are sufficient to do away with the overhaul of the older design part. Thus, at the beginning of year four, only parts from new procurement are introduced as replacements in the system. Over time, as these new parts are removed, they are then returned for overhaul and maintain the new higher reliability levels. However, it takes some time for those parts to begin appearing in the reverse logistics flow. Figures 18, 19, 20, and 21 present the simulation results for Scenario 3. Figure 18 illustrates the recurring demands level over time. Similar to Scenario 1, once the improved reliability parts are introduced, the recurring demands decline over approximately eight years as the part mix goes from all older parts to all newly designed parts. The overall dynamics of this scenario are more complex than in the first two scenarios. Figure 19 shows a decline in the procurement reorder point similar to that seen in Scenario 1. This decline in the “target” reorder point is due to the reduced demands arising from the more rapid introduction of improved parts than in Scenario 2. Figures 19 and 20 show a substantial growth in new procurement since overhaul parts are not used for some period of time. As in Scenario 1, the pipeline of improved parts (ordered two years previously in an era of higher demand) enters the supply system as demand is falling. As a result, as may be seen in Figure 21, there is a buildup of inventories. This leads then to a period of time with no orders for new parts. On the other hand, the total overhaul completion rate drops off completely for a few years because the older parts are not undergoing overhaul. After roughly six years, a sufficient number of new parts are being returned for overhaul and that overhaul program largely supports the demands for a period of time. Lastly, note in Figure 21 that the serviceable inventory level drops significantly at the beginning of year four because all of the old design parts are scrapped and production of new parts has not ramped up as quickly. Because only newly improved parts are entering the supply chain, there is a lag before the serviceable inventory begins to rise. The long lead times and lag periods account for the difficulty in planning and the complex dynamics.

Figure 22 presents the financial results for Scenario 3 including the base case and reliability improvement cases 1, 2 and 3. Note that the benefit to investment ratio is similar to Scenario 1 but much better than Scenario 2. Recall that in Scenario 1, all older parts were upgraded to the higher reliability design during the overhaul process. This means that starting in year four of Scenario 1, all parts being supplied have higher reliability and demand drops fairly quickly over a period of eight years. In Scenario 3, all new parts are being introduced with a corresponding rapid drop in demand. The key difference between Scenarios 1 and 3 is the higher cost of a new part compared to the cost of an overhauled part. This difference creates slightly lower savings for Scenario 3. Both Scenarios 1 and 3 have greater returns than Scenario 2 with the slow introduction of parts with improved reliability.

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Figure 18: Recurring Demands for Scenario 3

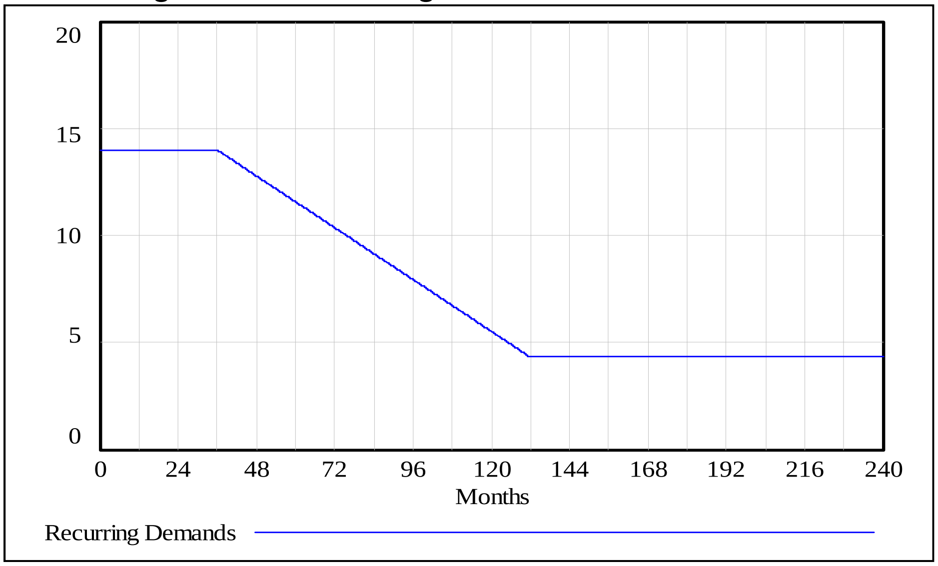


Figure 19: Procurement Actions for Scenario 3

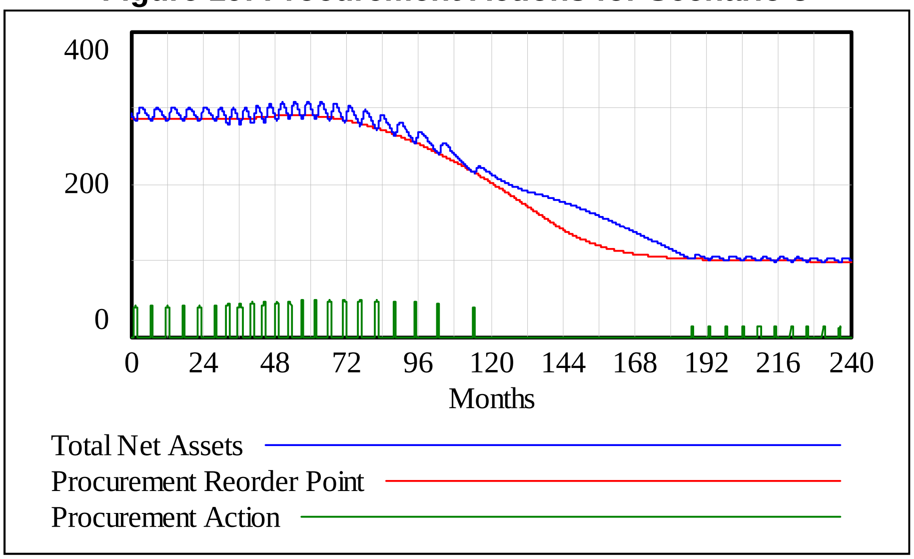


Figure 20: Overhaul and New Procurement Production Completion Rates

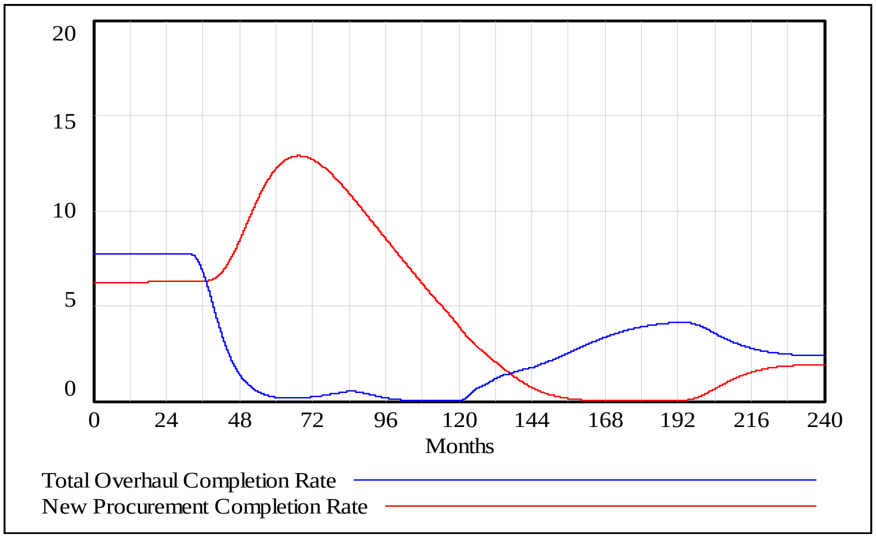


Figure 21: Inventories for Scenario 3

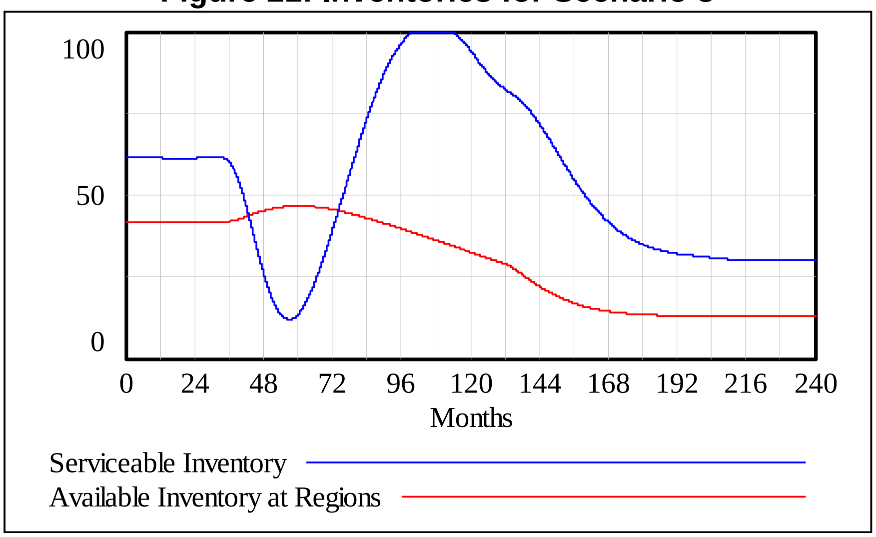


FIGURE 22: Financial Results for Scenario 3 Cases Base, 1, 2, and 3

Current Dollars Annual Spending Amounts ($Millions)*

	Percent Reduction in Failure Rate Per Flight Hour						
Year	Base Spend 0%	Case 1 Spend 60%	Case 1 Savings	Case 2 Spend 66.7%	Case 2 Savings	Case 3 Spend 69.2%	Case 3 Savings
1	$36.2	$37.8	-$1.6	$38.7	-$2.5	$39.5	-$3.3
2	$38.3	$40.1	-$1.8	$41.0	-$2.7	$41.9	-$3.6
3	$40.9	$42.7	-$1.8	$43.7	-$2.8	$44.6	-$3.7
4	$40.9	$40.9	$0.0	$40.9	$0.0	$40.9	$0.0
5	$37.6	$37.5	$0.1	$37.5	$0.1	$37.5	$0.1
6	$53.0	$51.1	$1.9	$50.9	$2.1	$50.8	$2.2
7	$63.2	$56.2	$7.0	$55.2	$8.0	$54.9	$8.3
8	$71.2	$53.6	$17.6	$51.5	$19.7	$50.7	$20.5
9	$78.3	$45.6	$32.7	$42.2	$36.1	$41.0	$37.3
10	$77.3	$36.4	$40.9	$32.4	$44.9	$30.9	$46.4
11	$74.5	$27.7	$46.8	$22.5	$52.0	$20.5	$54.0
12	$75.9	$24.6	$51.3	$18.5	$57.4	$16.3	$59.6
13	$77.3	$19.8	$57.5	$13.9	$63.4	$12.0	$65.3
14	$79.4	$20.6	$58.8	$15.1	$64.3	$13.2	$66.2
15	$82.5	$25.1	$57.4	$19.6	$62.9	$17.6	$64.9
16	$86.3	$30.7	$55.6	$23.6	$62.7	$21.6	$64.7
17	$92.8	$35.9	$56.9	$27.9	$64.9	$24.5	$68.3
18	$98.5	$39.3	$59.2	$32.1	$66.4	$28.3	$70.2
19	$104.8	$42.2	$62.6	$35.3	$69.5	$32.2	$72.6
20	$112.0	$45.0	$67.0	$37.6	$74.4	$34.8	$77.2
Cumulative	$1,420.9	$752.8	$668.1	$680.1	$740.8	$653.7	$767.2

Investment Over Three Year Period (Years 1 - 3)**				
Case 1 $5 Million	Break-Even (Years)	3.43		
Case 2 $7.5 Million	Break-Even (Years)		3.66	
Case 3 $10 Million	Break-Even (Years)			3.93

Ratio of Benefits to Investment***			
Case 1 $5 Million	133.6		
Case 2 $7.5 Million		98.8	
Case 3 $10 Million			76.7

*Annual spending amounts include investment spending during first three years

**Breakeven period is the time required to recapture the investment through savings after the investment period

***Benefits are the total cumulative savings

Sensitivity and Comparative Analysis

Figure 7 presented an empirically derived relationship between percentage improvement in reliability and the ratio of investment to part cost. As indicated earlier, this relationship was used to determine the reliability impacts on a part costing $250,000 arising from investments of $5, $7.5 and $10 million to improve reliability. From Figure 7, for a part costing $250,000 these investments would lead to reliability improvements of 150%, 200% and 225%. These improvement levels were the alternative cases used for the three overhaul scenarios. Figures 23, 24 and 25 present reduction in lifecycle spending and the benefit to investment ration for a wide range of investment ratios, going from zero to 800, that is, an investment 800 times the cost of the product. Results are presented for the three overhaul scenarios. These charts present the investment ratios, the resultant reliability improvement ratios, and from the simulation results, the total cumulative spending, the percent reductions in lifecycle spending and the benefit (savings) to investment ratios for both constant and current dollars.

FIGURE 23: Scenario 1
Old Parts Undergo Overhaul, are Upgraded in Overhaul and are Re-Issued with New Improved Level of Reliability

		Constant Dollars			Current Dollars		
Investment/ APUC	Reliability Improvement Ratio*	Total Spend ($millions)**	Percent Reduction in Spending (%)***	Benefit/ Investment Ratio****	Total Spend ($millions)	Percent Reduction in Spending (%)	Benefit/ Investment Ratio
0 (Base)	0.0	$724	-	-	1,357	-	-
20 (Case 1)	1.5	$423	42%	60.2	$702	48%	131.0
50	2.5	$372	49%	28.2	$582	57%	62.0
100	3.5	$353	51%	14.8	$521	62%	33.4
200	5.0	$359	50%	7.3	$507	63%	17.0
400	7.0	$393	46%	3.3	$523	61%	8.3
800	9.0	$478	34%	1.2	$600	56%	3.8

FIGURE 24: Scenario 2
Old Parts Undergo Overhaul But Are Not Upgraded in Overhaul and Are Re-Issued with Old Reliability

		Constant Dollars			Current Dollars		
Investment/ APUC	Reliability Improvement Ratio*	Total Spend ($millions)**	Percent Reduction in Spending (%)***	Benefit/ Investment Ratio****	Total Spend ($millions)	Percent Reduction in Spending (%)	Benefit/ Investment Ratio
0 (Base)	0.0	$724	-	-	1,357	-	-
20 (Case 1)	1.5	$516	29%	41.6	$886	35%	94.2
50	2.5	$483	33%	19.3	$798	41%	44.7
100	3.5	$474	35%	10.0	$757	44%	24.0
200	5.0	$484	33%	4.8	$750	45%	12.1
400	7.0	$521	28%	2.0	$772	43%	5.9
800	9.0	$610	16%	0.6	$855	37%	2.5

FIGURE 25: Scenario 3
All Old Parts are Scrapped and Do Not Undergo Overhaul, New Production Ramps up to Overcome Loss of Overhaul Supply Stream

		Constant Dollars			Current Dollars		
Investment/ APUC	Reliability Improvement Ratio*	Total Spend ($millions)**	Percent Reduction in Spending (%)***	Benefit/ Investment Ratio****	Total Spend ($millions)	Percent Reduction in Spending (%)	Benefit/ Investment Ratio
0 (Base)	0.0	$763	-	-	1,421	-	-
20 (Case 1)	1.5	$455	40%	61.6	$753	47%	133.6
50	2.5	$403	47%	28.8	$631	56%	63.2
100	3.5	$382	50%	15.2	$568	60%	34.1
200	5.0	$388	49%	7.5	$551	61%	17.4
400	7.0	$419	45%	3.4	$564	60%	8.6
800	9.0	$505	34%	1.3	$638	55%	3.9

*Derived from Figure 7
**Investment amount included in Total Spend amount
***Calculated by dividing total benefit (savings) by Base Case Total Spend amount
****Calculated by dividing total benefit (savings) by investment amount

The results in Figures 23, 24 and 25 are presented as graphs in Figures 26 through 29. Figures 26 and 27 clearly show that the maximum percent reduction in spending is achieved at an investment ratio of approximately 100. Below this level of investment, potential benefits are being left on the table. Above this ratio, diminishing returns are evident in that the higher and higher investments are not generating the sufficient benefits to overcome the large investments. Figures 28 and 29 present the return on investment defined as the ratio of benefits (savings) to investment. As may be seen, these returns fall off sharply as the investment increases. Note that these are benefit ratios, not percentages, so that for an investment ratio of 100 the benefit ratio ranges between ten and fifteen (using constant dollars) for a return percentage of 1,000% to 1,500%. The returns are so substantial because twenty year lifecycle spend reductions are very large, ranging from $700 to $900 million for a single part that costs $250,000. These results dramatically illustrate the benefits that are possible by improving reliability.

FIGURE 26: Constant Dollars Percent Reduction in Spending as a Function of Investment in Improved Reliability

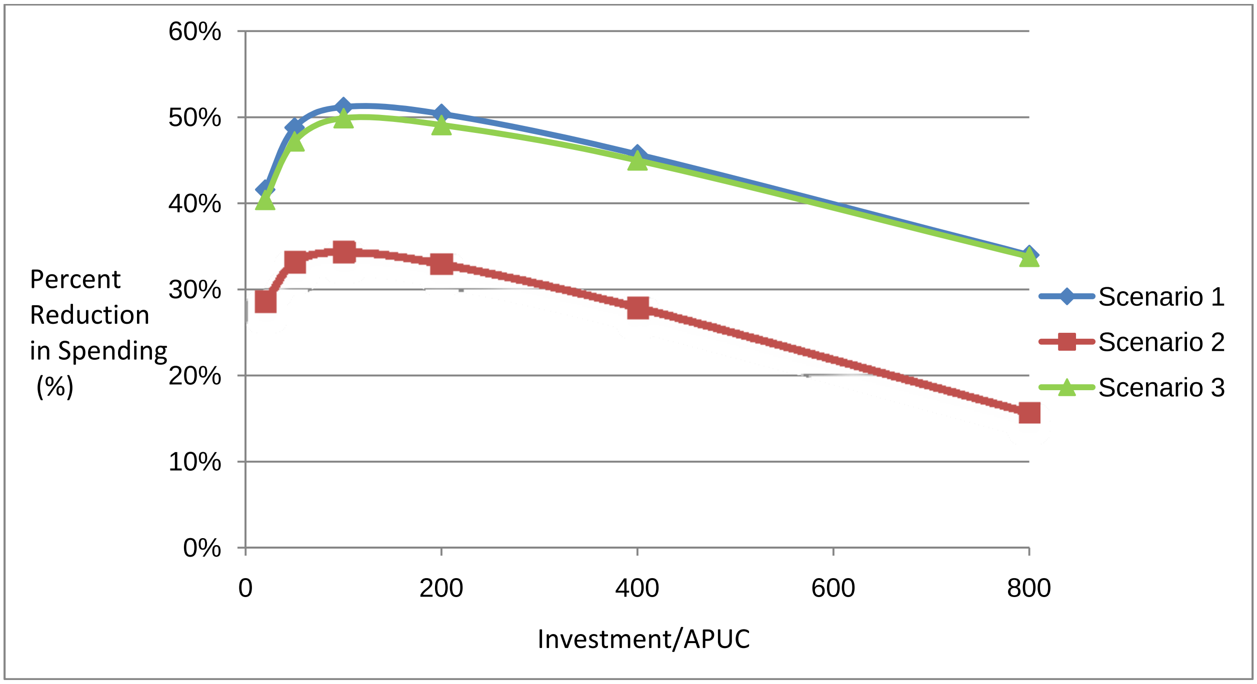


FIGURE 27: Current Dollars Percent Reduction in Spending as a Function of Investment in Improved Reliability

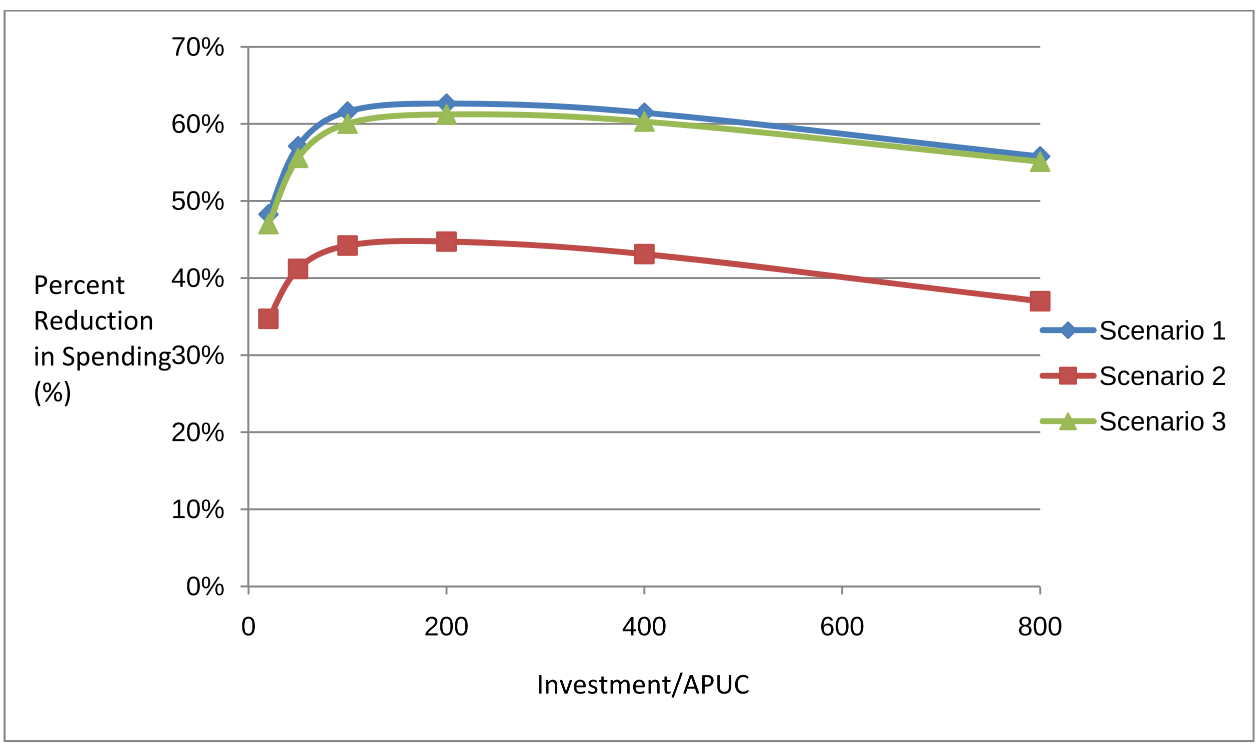
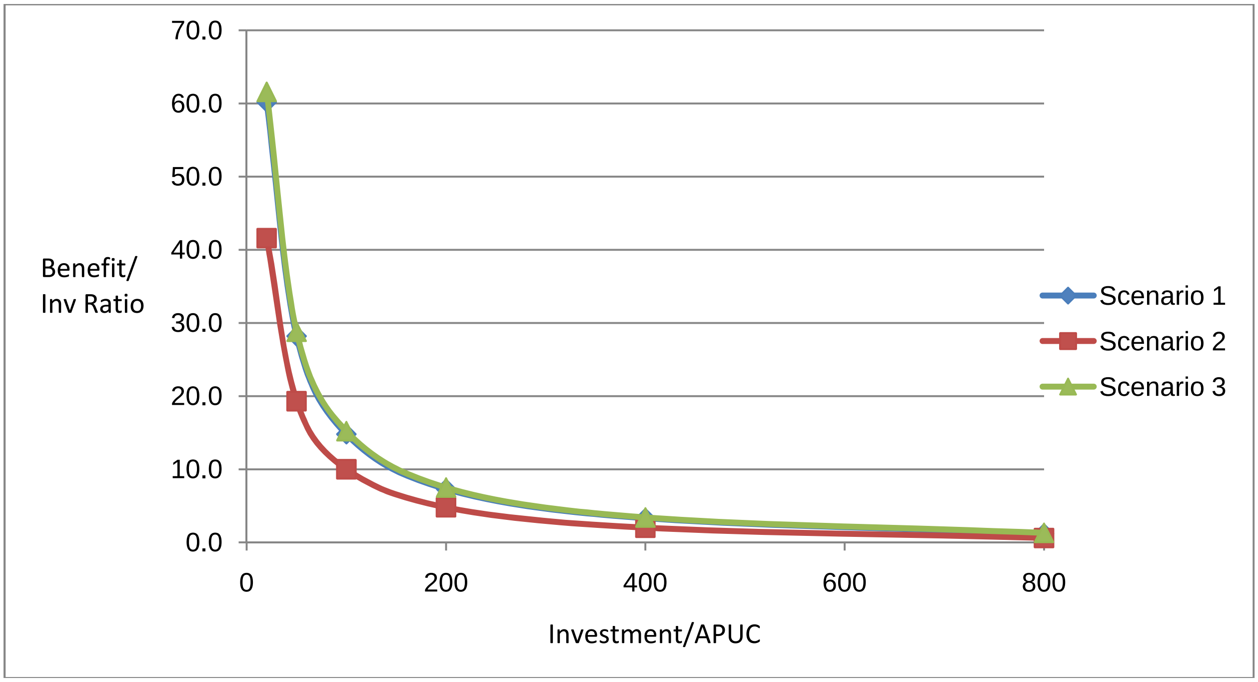
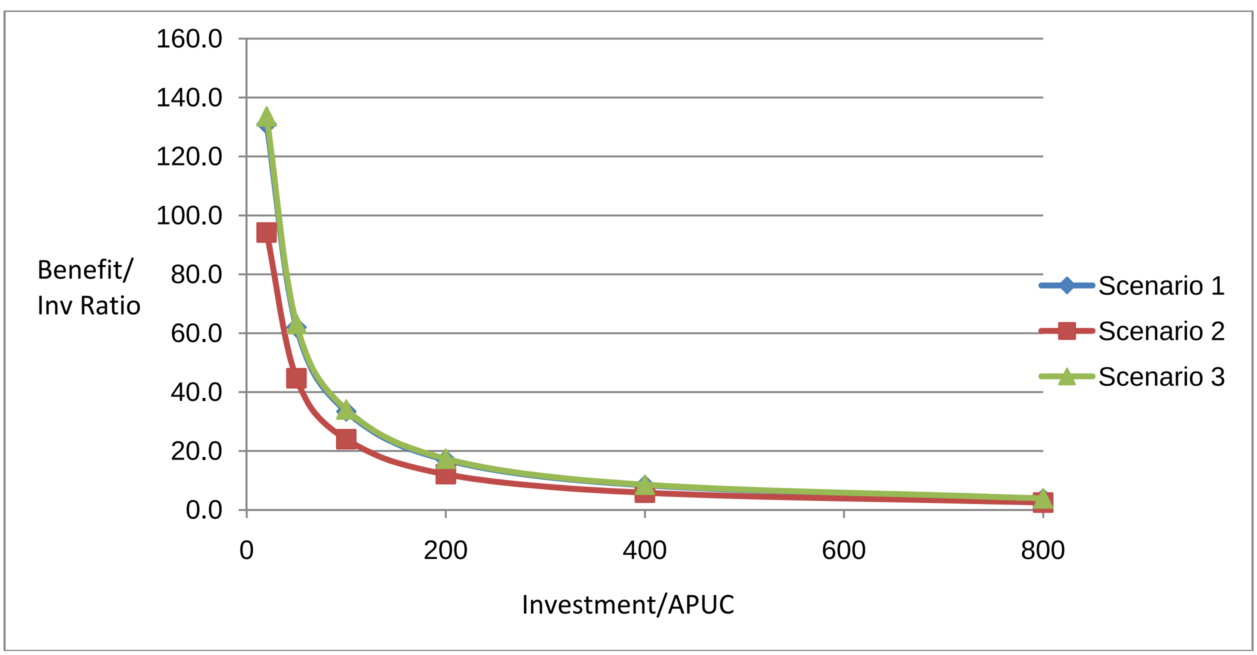


FIGURE 28: Constant Dollars Benefit/Investment Ratio as a Function of Investment in Improved Reliability*



*NOTE: Scenario 1 and 3 overlap in the figure above.

FIGURE 29: Current Dollars Benefit/Investment Ratio as a Function of Investment in Improved Reliability*



*NOTE: Scenario 1 and 3 overlap in the figure above.

Conclusion

Maintaining military aircraft in a high state of readiness requires a non-stop flow of spare parts. When parts must be removed, there are two primary sources for the replacement parts: new parts from procurement or repaired parts coming from overhaul. The costs associated with the acquisition, overhaul, transportation and labor to remove and install these parts are a significant part of a system's total Operations & Support (O&S) costs. Moreover, these O&S costs generally account for 70% to 80% of total lifecycle costs, and, as a result, much attention has been directed recently towards the reduction of O&S costs in Defense budgets. One important approach for reducing O&S costs is to improve reliability. A part with higher reliability is replaced less often, thus, reducing maintenance labor and the required flow of new and repaired replacement parts. This reduction in the on-going supply of replacement parts potentially, but not necessarily, reduces O&S costs. The overall cost impact depends upon any increase in the cost of the new improved part, the increase in reliability, the demand level and whether older parts can be transformed to the new more reliable design through overhaul. Even if costs are reduced, it may not be a sound business decision depending upon the required investment. Business case analyses must answer the questions: "What are the reductions in lifecycle costs arising from an investment in reliability improvement and what are the return and payback time for the required investment and what role does overhaul play in determining lifecycle returns?"

Three overhaul scenarios have been examined to evaluate the payback and returns generated by investments to improve the reliability of certain aviation parts. These scenarios are:

1. Older parts can be transformed during the overhaul process into the new design with improved reliability. Thus, both the new parts coming from acquisition and the parts coming from overhaul now both possess the improved reliability.
2. The older parts cannot be transformed into the new parts but there is either insufficient production capacity or funding to provide for all new parts. As a result, the old parts go through overhaul and are re-issued but with the old level of reliability.
3. The older parts cannot be transformed into the new parts but there is sufficient funding and production capacity for new parts to make up for the lost overhaul source. In this case, all old parts are scrapped. As a result, all parts being issued are new and possess higher reliability.

A system dynamics supply chain and financial model was developed to investigate these scenarios through simulation. This model incorporates the requirements determination process that controls many government supply chains in a feedback fashion. It is shown using the model that all three scenarios reduce total lifecycle costs and that these reductions can be very significant. The system dynamics supply chain and financial simulation model demonstrates how these lifecycle cost reductions depend upon the levels of reliability, investment amounts and the role of overhaul.

The lifecycle simulations show that the financial results are somewhat similar for Scenarios 1 and 3. These scenarios are similar because, after year four, all parts being issued have the improved reliability. It must be noted that Scenario 1 can be difficult to implement because it assumes the older parts can be upgraded to the new improved reliability level during overhaul. If design changes are significant this may not be possible. Scenario 3 assumes all older parts are scrapped and that production capacity can be increased to make up for the lost overhaul. Again, this scenario may be difficult to implement either because of funding limitations or because of the production constraints of the US industrial base. In general, overhaul Scenario 1 financially outperforms the other two scenarios, although Scenario 3 is often very competitive. Since in Scenario 3, all parts being issued are newly procured parts, the annual spending amounts are higher based on the original assumption that new parts are more expensive that repaired parts. Scenario 2 offers the lowest potential for cost savings since old parts emerge from overhaul with the old level of reliability. This delays the realization of lower demands and the financial benefits. In Scenarios 1 & 3 the changeover between old and new parts in the population requires about eight years. In Scenario 2, the changeover requires about sixteen years since older parts are re-issued from overhaul with the old reliability level.

Although all scenarios have relatively quick payback ratios, Scenario 1 recaptures its investment the quickest. Since Scenario 1 allows initial parts to be upgraded and returned for service at the new reliability level, fewer funds are used to buy solely new procured parts (Scenario 3). This unique capability allows the overhaul process of Scenario 1 to endure greater cost savings immediately after the investment period as compared to Scenario 3.

All scenarios illustrate that improvements in reliability can greatly reduce the total costs. However, it is noted that the possibility for cost reductions cannot continue to increase forever. Diminishing returns exist as the investment amount grows past a certain amount. If the investment amount is too substantial in size, costs savings can still be achieved but not in the most efficient form. O & S costs may be greatly decreased in size, but excessive investment and production costs will counteract the main goal of reducing total lifecycle costs. The analysis shows clearly that the maximum percent reduction in spending is achieved at an investment ratio of approximately 100. Below this level of investment, potential benefits are being left on the table. Above this ratio, diminishing returns are evident in that the higher and higher investments are not generating the sufficient benefits to overcome the large investments. It is shown that returns fall off sharply as the investment increases. Note that these are benefit ratios, not percentages, so that for an investment ratio of 100 the benefit ratio ranges between ten and fifteen (using constant dollars) for a return percentage of 1,000% to 1,500%. The returns are so substantial because twenty year lifecycle spend reductions are very large, ranging from $700 to $900 million for a single part that costs $250,000. These results dramatically illustrate the benefits that are possible by improving reliability and the important role that overhaul plays in achieving these benefits.

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