Using System Dynamics to Estimate Reductions in Life-Cycle Costs Arising From Investments in Improved Reliability

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Abstract

"Doing more with less" has become a long-running and recurring theme across the globe. Affordability is now a key metric for operations and sustainability, and reliability is now seen as a key driver of these lifecycle costs. A system dynamics model has been developed of an aviation supply chain that enables evaluation of alternative cases in which investments are made to improve reliability, lower total demands, and reduce spending on new procurement and overhaul over the lifecycle. It is shown that the payback potential of an investment depends upon annual demand for the part, cost of the part, percent improvement in reliability achieved, and any increase in cost of the part due to the re-design. The analysis show that returns can be high and payback periods can be fast, particularly for investments to improve reliability of items with high demand and high cost. The research also indicates that close coordination is needed between program management, procurement planning and acquisition in order to fully realize savings. Ongoing research is developing reliability investment strategies and estimates for lifecycle costs under differing demand, manufacturing and overhaul scenarios.

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

Introduction

“Doing more with less” has become a long-running and recurring theme across the globe. Companies, government agencies and even charities are being forced to deliver higher performance with reduced funding and capital. (Ain, 2009; Anthony, 2009; Shute, 2009; Gottlieb, 2008) This challenge is especially acute for the US Department of Defense and the branches of the armed services where demands are great and budgets are tight. As long ago as 1995, Dr. Paul Kaminsky, then the Under Secretary of Defense for Acquisition and Technology, stated that a key goal “…is a simple one of trying to do more with less.” This objective has steadily become more critical over the last fifteen years and has led to on-going efforts to achieve efficiencies while at the same time maintaining availability and system readiness. Because typically the costs to operate, maintain, and dispose of a weapon system account for about 72 percent of the total cost of ownership, much effort has focused on these expenditures. (GAO-03-57) The DoD Reliability, Availability, Maintainability, and Cost Rational Report Manual (2009) states the issues succinctly:

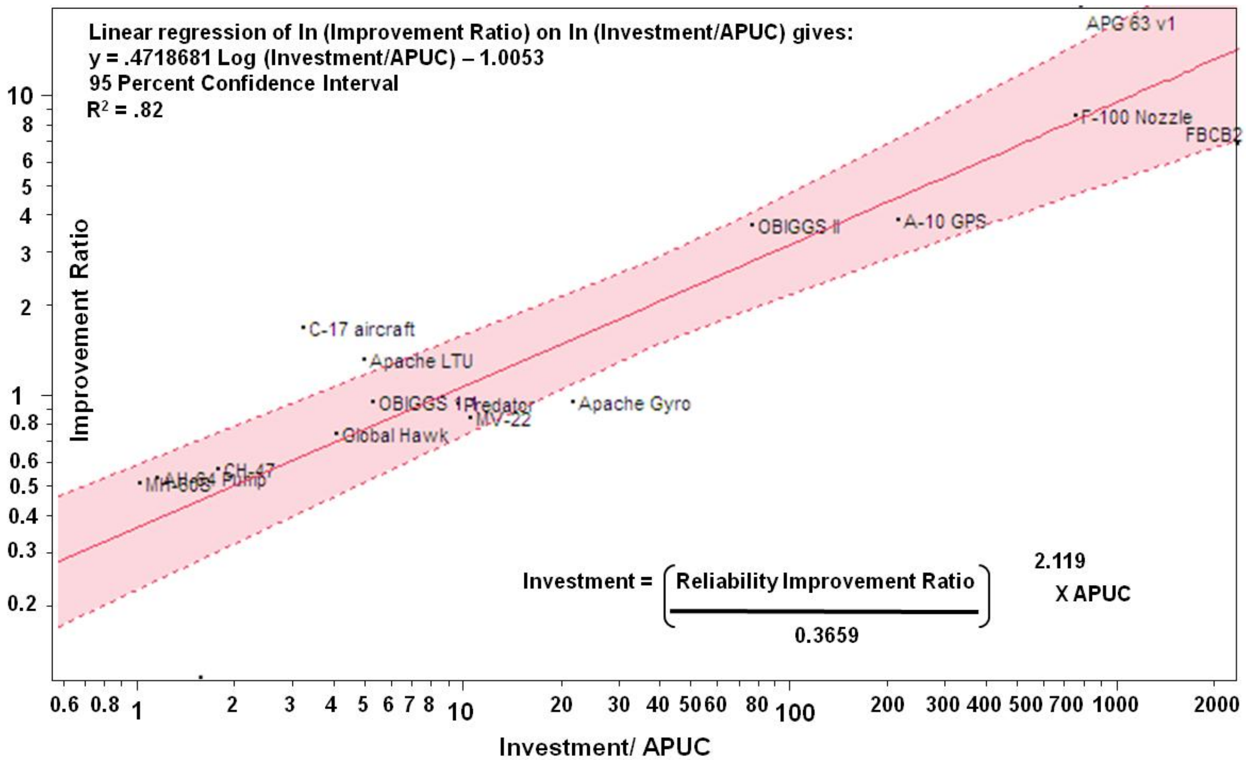
> The Department of Defense (DoD) needs to acquire reliable and maintainable products that are of high quality and readily available to satisfy user requirements in meeting mission capability and operational tasks. The Department must acquire these products at the most reasonable cost to the taxpayer. The cost to the government, however, is not just computed by the procurement costs, but also must balance the long-term costs incurred in maintenance, driven by reliability, availability, and other factors throughout the system life cycle.

Improvements in reliability have multiple cost saving impacts such as fewer parts to buy and overhaul, smaller inventories of replacement parts, fewer inspections, reduced maintenance hours and down time, reduced transportation costs to ship replacement parts, and on and on. Nevertheless, recent research found the following to be the case:

> Test results since 2001 show that roughly fifty percent of DoD’s programs are unsuitable at the time of initial operational test and evaluation, because they do not achieve reliability goals. This represents a significant and alarming change in the number of programs found unsuitable as compared to historical levels. Because reliability is a prime determinant of long-term support costs, delivered reliability so far off the mark has serious consequences for both operational suitability and affordability. (Forbes, Hees, Long, and Stouffer, 2007)

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 1 and is taken from a presentation delivered by Mr. Charles E. McQueary, Director, Operational Test and Evaluation.

Figure 1: 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 1, 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.

It should be noted that this chart relates reliability investments to reliability improvements but does not take the next step and relate investments in reliability to reductions in life-cycle costs. Additional research is focusing on that next step using the Cost Analysis Strategy Assessment (CASA) model, a total life-cycle cost analysis tool, and other analytical techniques. (Forbes, Hees, Long, and Stouffer, 2007) Such models give estimates for changes in twenty year support costs based upon a variety of input assumptions including changes in reliability. These models, however, do not give indications of changes in readiness levels or of payback time for the investment. According to the Department of the Army Economic Analysis Manual, the Break Even Point (Payback period) is an important metric for investments. For example, two investments might have similar benefit cost ratios or similar savings to investment ratios, but if one has a substantial faster payback, it is the superior investment. Both the readiness and time dynamic aspects of reliability investments need to be included in a benefits analysis.

One approach to investigating sustainment costs that incorporates both readiness and time of payback is to view the support process as an on-going enterprise supply chain that provides new parts, repair, support, maintenance, etc. over the operating life cycle. Improvements in reliability clearly affect the operational aspects of the supply chain through reductions in removals, overhaul requirements, new spare acquisitions, shipment of replacements and all of the associated and related costs. Simulation of this enterprise using a dynamic modeling approach can establish a relationship between improvements in reliability and reduced operating costs as well as indicating changes in readiness levels and time of payback.

Analytical Approach

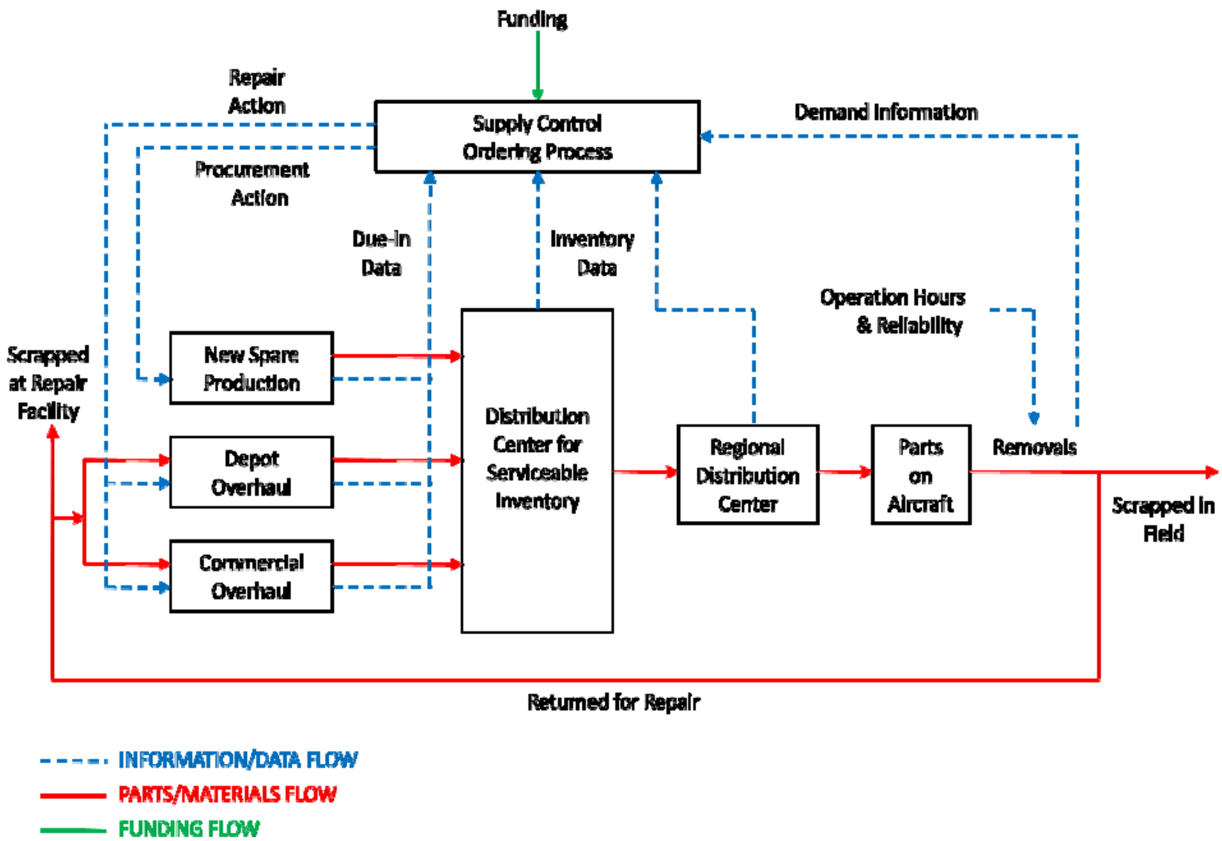
System Dynamics is a well-suited tool for understanding the structure and dynamics of complex supply chain systems and the factors over time determining lifecycle costs. From its very beginning, System Dynamics has been used to analyze supply chains as a modeling and simulation tool for policy analysis. 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, however, 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 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. Schroeter and Spengler (2005) addressed the strategic management of spare parts in closed loop supply chains. Angerhofer (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. The intent of the current research is to analyze the impacts of improvements in reliability on supply chain behavior and lifecycle costs using a system dynamics model. By using appropriate discount and inflation rates, cumulative and annual costs are measured in relation to investment amounts to weigh the overall benefits for improvement in the government supply chain.

Model Description

An overview of the supply chain for high-value aviation parts is shown in Figure 2. This diagram illustrates the flow of parts from new production and overhaul to the final customer. The overall supply chain process is managed in a feedback form by the government's ordering or requirements determination process. 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 2: Overview of Supply Chain Model

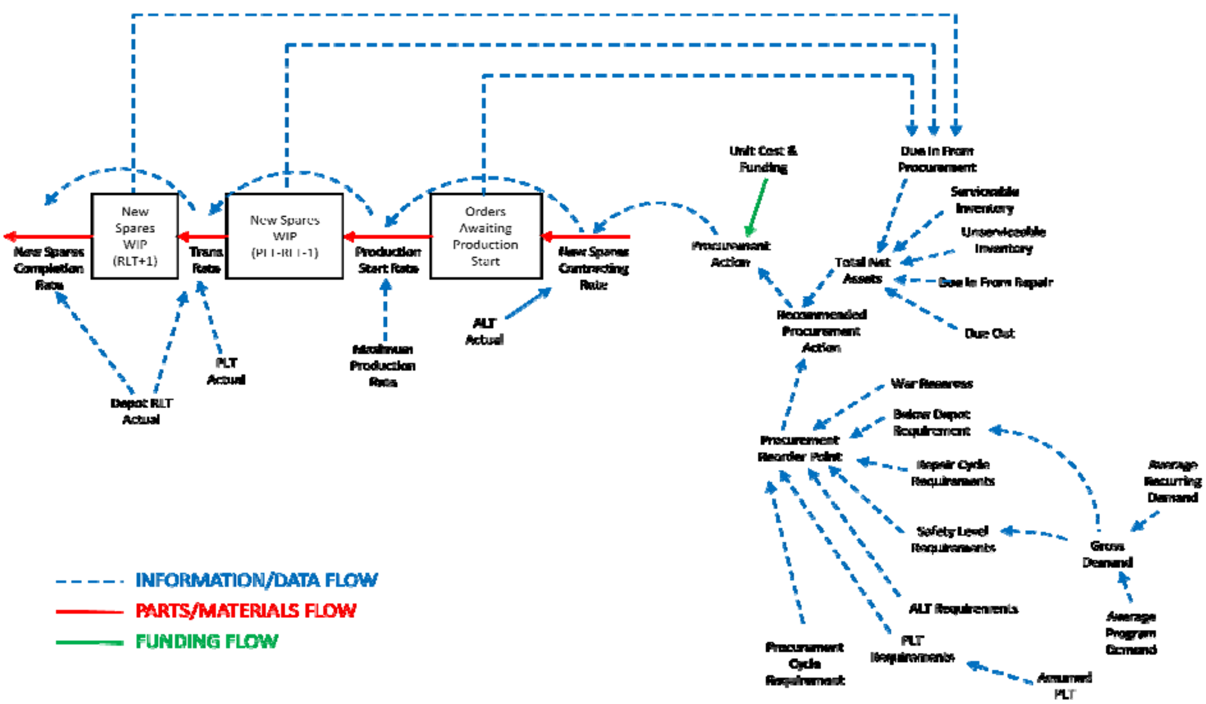


By systematically comparing current levels of inventory, due-ins, due-outs, and historical demand levels, the ordering process determines the recommended buys and repairs. The demand for a part is driven by the total number of installed parts, monthly operating hours, and failure rate per part per operating hour, sometimes expressed as a mean time between failures (MTBF). The supply of parts comes from three possible sources: production of new items, commercial overhaul of damaged parts, and government overhaul of damaged parts. Once the production or overhaul process is completed, parts are then transferred to the central distribution inventory. Each region has an inventory of key spare parts, and these inventories are replenished from the central distribution inventory. Parts excessively damaged and unable for repair may be scrapped at two different points once they are removed from the aircraft. The first possibility is for parts to be scrapped in the field and not be returned for overhaul. The second possibility is for parts to be scrapped at the repair facility be it either at a depot or commercial manufacturer.

Several levels of calculation are incorporated into the supply control ordering process to determine recommended buys and repairs. (Killingsworth, Chavez, and Martin, 2008)

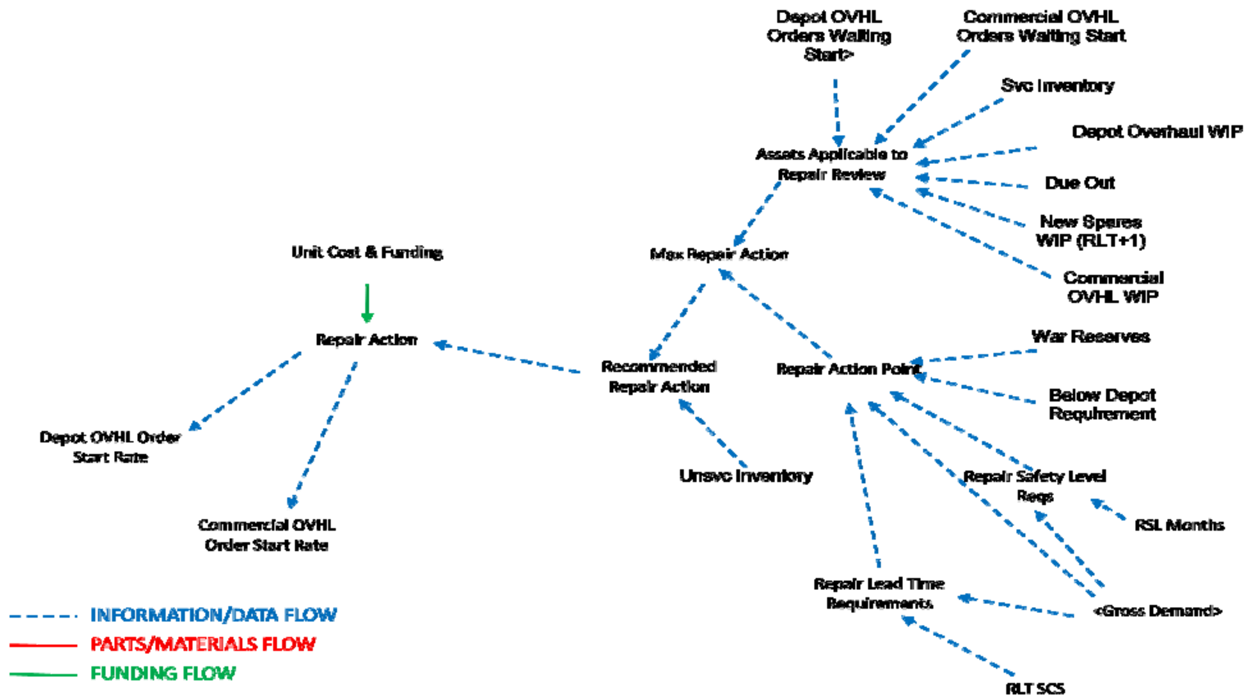
The determination process calculates the procurement action for new spare parts by calculating the difference between the procurement reorder point and the total net assets, and then adding the procurement cycle requirement and the inventory necessary to meet demands until the next scheduled order. Total net assets are calculated from due-ins from procurement and repair plus inventories, less due-outs. The procurement reorder point is based on targeted reserves and safety levels. Within the model, orders that are placed with the OEM enter production subject to a maximum production rate and availability of all the required components. Production is completed after a manufacturing lead time. After production, these new parts flow into the distribution center for serviceable inventory. Figure 3 illustrates the recommended new spares procurement action.

Figure 3: Recommended New Spares Procurement Action



The determination for recommended repair action differs in an important way from the determination of the recommended procurement action. First, the maximum recommended repair action is calculated by subtracting the assets available for repair, including overhaul and procurement work-in-process less due-outs, from the repair action point, calculated with reserve levels and safety requirements. This process is largely driven by historical demands. In the second step, the maximum recommended repair action, however, is then limited by the unserviceable inventory on hand. A damaged part must be available for repair or overhaul to take place. The potentially constrained repair order is allocated between government depot and commercial overhaul according to capacity levels at each location. The overhaul rates may also be limited by production capacity levels. Similar to procurement production, once overhaul is complete, the part is transported to the distribution center for serviceable inventory. Figure 4 illustrates the process for calculating the recommended repair action.

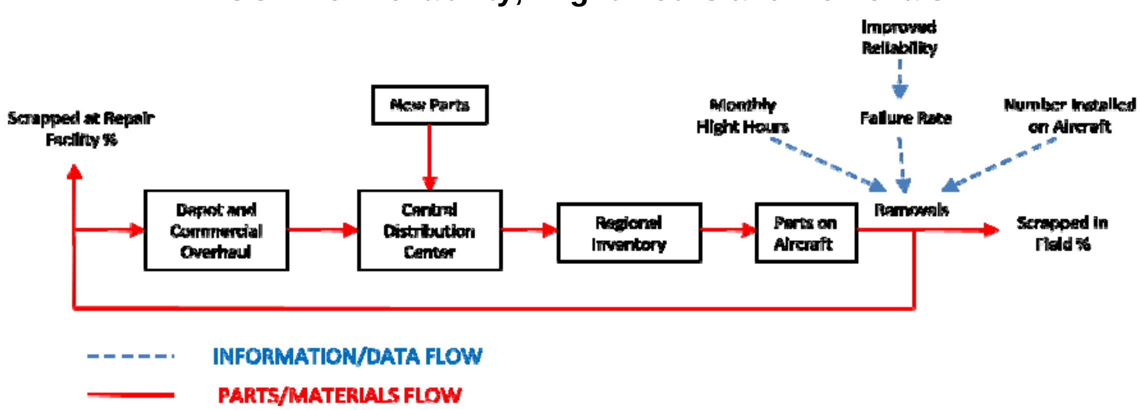
FIGURE 4: Recommended Repair Action



Upon arrival at the distribution center for serviceable inventory, all parts, both new and repaired, are available for shipment to the regional inventory centers.

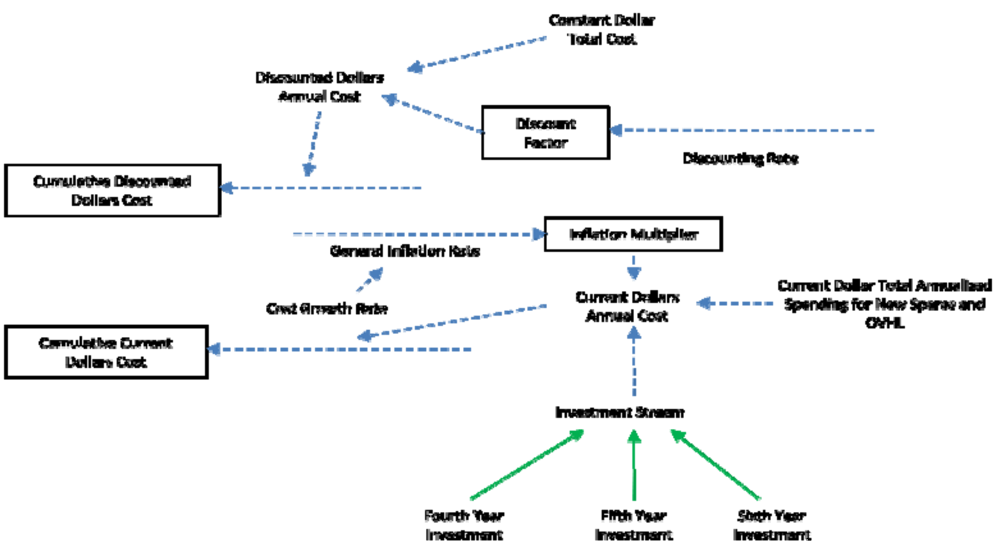
The regional inventory center orders parts from the central distribution center to replenish that inventory being used to replace removed parts. The monthly removals are dependent upon the number of parts in service (i.e. number installed on aircraft), the monthly operational hours (i.e. monthly flight hours), and failure rate per monthly operational hour. Hence, if reliability is improved, the failure rate per flight hour is reduced, demand is reduced and pull from inventories is reduced. This leads to reduced orders for new spares and overhaul. This high level view of the model structure is shown in Figure 5.

FIGURE 5: Reliability, Flight Hours and Removals



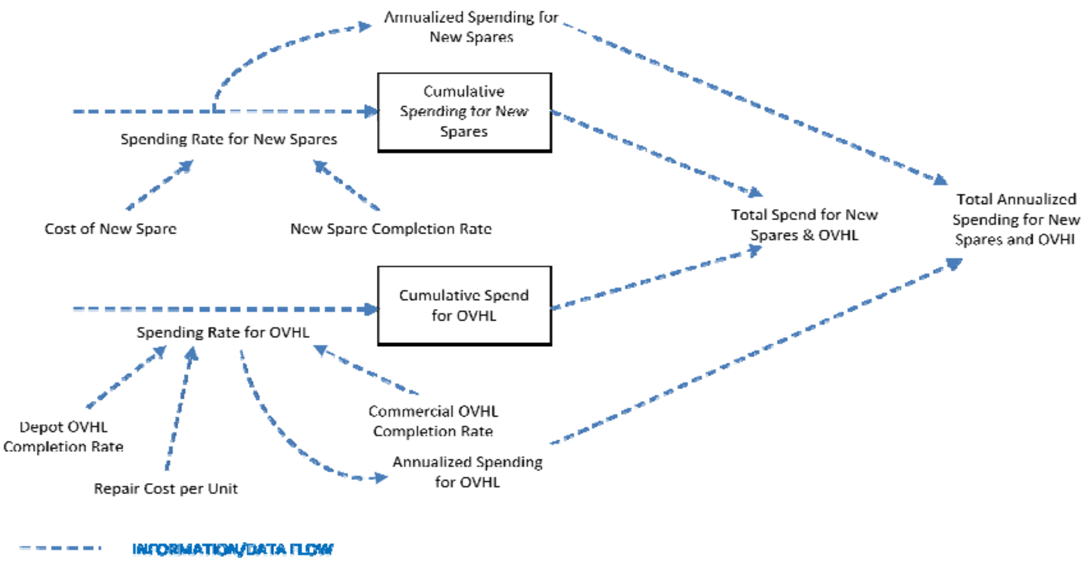
The objectives of this research are to determine how investments in reliability improvement can reduce life-cycle costs and improved readiness. It is assumed in the model that the investment occurs over a three year period that includes design, manufacturing, test, and certification. Shorter or longer investment scenarios are easily included and examined in the model structure. Figure 6 illustrates this structure for the simulation, and the factors involved in calculating annual current dollar, constant dollar, and discounted dollar expenditures as well as life-cycle cumulative costs. The figure also illustrates how the discount and inflation rates are used in the calculation for constant dollars (Constant year dollars are the result of having the effects of inflation removed. Constant year dollars are always associated with a base year.), discounted dollars (Discounted dollars are the present value of a cost made in the future.), and current dollars (Current year dollars are expressed in the value of the year of in which a cost is expected to occur, and therefore reflect the effects of inflation).

FIGURE 6: Investment for Improved Reliability



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. Figure 7 illustrates the calculation in the model of cumulative spending and annualized spending.

FIGURE 7: Cumulative and Annualized Spending



Evaluation of Alternative Investments

The key objectives of the analysis were twofold:

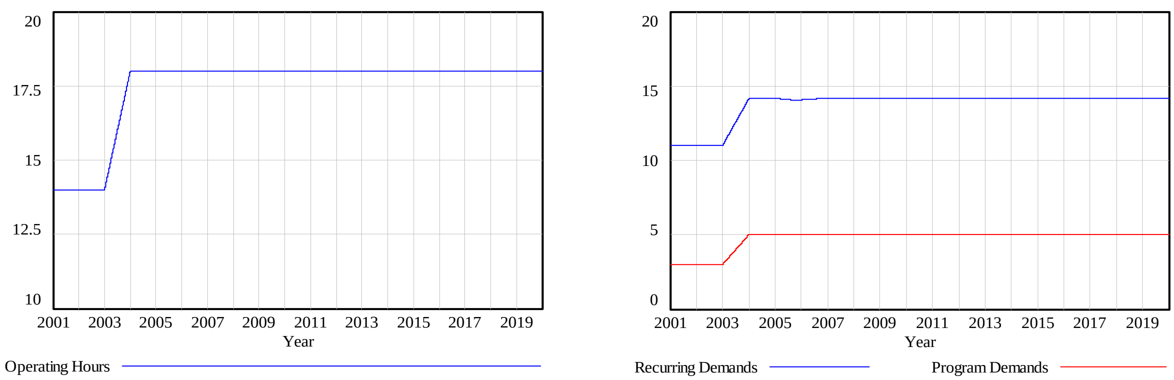
(i) First, to determine the reductions in life-cycle costs and payback periods for investments in reliability using "what if" assumptions relating the improved reliability and the assumed level of investment. In these analyses, payback is determined and life-cycle costs are calculated assuming for example that a $10 million dollar investment will generate a 10% improvement in reliability. The simulation can then be conducted assuming that the $10 million produces a 20% increase in reliability. These types of analyses allow one to determine the required reliability improvement of an investment such that an adequate return is generated through reductions in life-cycle costs. This enables a business case analysis to be completed for a proposed program.

(ii) Second, to determine the reductions in life-cycle costs and payback periods for investments in reliability using empirical data developed in previous DoD research that relates investment as a percentage of unit cost to improvements in reliability. This analysis can then supplement and support a business case analysis as conducted above.

In the first part of the investigation, the model structure was parameterized for a major repairable helicopter part. The simulation begins 1January 2001. Demands in 2001 and 2002 were fairly stable as were inventories. However, with the onset of the conflict in Iraq, demands rose sharply in 2003 and have remained elevated. As a result of the increased demands, inventories of many aviation parts were seriously depleted for a period of three to four years. For the part in question, the Production Lead Time (PLT) was roughly 24 months. Because of this long lead time, inventories for this part were reduced to near zero levels. A key validation test of the model was the ability to capture these dynamics. In the simulations for exploring improvements in reliability, it is assumed that investments in reliability were initiated in 2003 and extended through the end of 2005, a three year investment period. The improved part becomes available at the beginning of 2006. The time span for this simulation was selected in order to simulate an initial steady level in demand, then a significant surge in demand and to investigate the likely impacts of improved reliability on inventory recovery and cost reductions.

All cases assume stable demand levels from year 2001 to the beginning of 2003. In addition, all cases include a rise in demand beginning in year 2003 due to an increase in operating flight hours. In 2003, flight hours increase from 14 hours per aircraft per month to 18 hours per aircraft per month. Figure 8 presents operating hours per month over the simulation. It is important to note that this assumption for flight hours is the major external assumption driving the simulation and that this assumption can be easily altered.

FIGURE 8 & 9: Operating Hours Per Month Per Aircraft and Monthly Demands



The flight hour assumption and the failure rate per flight hour yields an initial monthly demand of eleven that increases to fourteen following the increase in flight hours. In addition to these recurring demands, it is assumed in the model that the part has an initial monthly program demand of three and that the program demand increases to five during 2003. These program demands arise through programs such as Reset and Recapitalization and are independent of flight hours. The demand assumptions are shown in Figure 9. For the simulation, it is assumed that with growing demands, an investment program is undertaken to improve reliability.

Note again that for those cases assuming a reliability investment, the investment is equally divided over three years (2003-2005 in these simulations). Starting in 2006, the introduction of the part with improved reliability begins to reduce demands, support inventory levels, and reduce procurement and repair actions. It is assumed in the model that the new parts are introduced through attrition. That is, as older parts are removed, they are replaced with the improved part. It is assumed that the removed parts which are not scrapped are transformed in the overhaul process to the part configuration with higher reliability. Current research is addressing the case in which this improvement is not possible in the overhaul process. The complete turnover in parts requires approximately eight years given the demand level in Figure 9. Thus, the overall transition to the improved MTBF occurs over that period of time.

In some of the alternative cases with improved reliability, an increase in the cost of the part is assumed. In these cases, the cost increase takes effect in year 2006 as the new parts are introduced. Table 1 presents the key assumptions for five reliability cases to be analyzed through simulation.

Evaluation of Investment in Reliability

TABLE 1: Cases for Improved Reliability

Case	Reliability Investment	Improvement in Reliability (MTBF)	Parts Cost Increase
1	No	0%	0%
2	Yes	33%	0%
3	Yes	33%	15%
4	Yes	50%	0%
5	Yes	50%	15%

Case 1: Base Case Analysis: No investment in reliability, no improvement in reliability, and no increase in parts cost; This Simulation Should Reflect Actual Supply Chain Performance;

Case 1 was conducted to provide a base case for inventory levels and procurement and repair actions over time. Cases 2-5 with improved reliability may then be compared to this base case. Figures 10 – 12 present the results of Case 1. As seen in Figure 10, the surge in demand in year 2003 causes a dramatic reduction in serviceable inventories. This decline in inventories creates backorders in the system, as orders cannot be completed due to lack of supply in inventory. In Figure 11, new procurement remains steady for the first four years, but ultimately ramps up due to the increase in demand arising from the greater number of flight hours. The delay in this ramp-up arises from the fact that the requirements determination process uses a twenty-four month rolling average for demand calculations. This rolling average only slowly reflects the higher demand levels. On Figure 11, the green tick marks represent procurement orders that arise as the total net assets level drops below the requirements objective. In Figure 12, the max repair activity rises sharply due to increased demand. The maximum repair activity represents the repair action that the system would optimally like to realize, but that action cannot be executed due to the lack of unserviceable inventory. Even though the max repair action is quite high, only the available unserviceable parts can be repaired, and the repair action remains at a modest level constrained by the flow of returning parts for overhaul.

Figure 10: Case 1 Inventory Levels

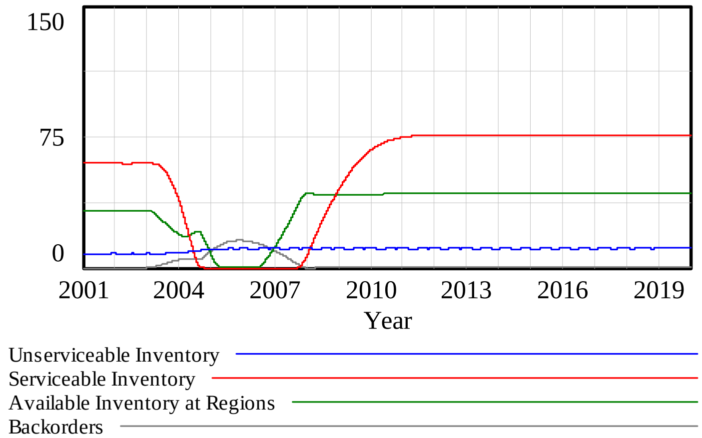


Figure 11: Case 1 Procurement Action

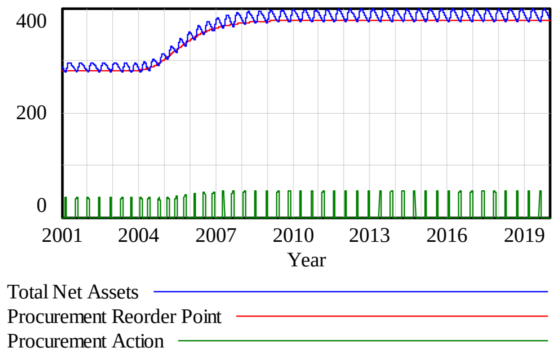
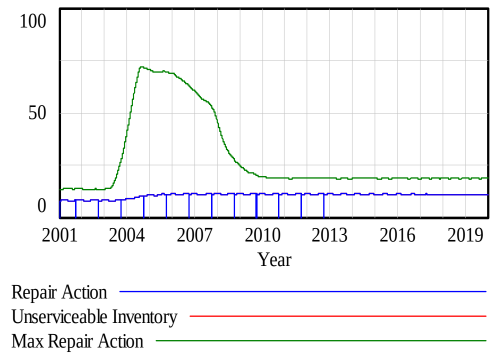


Figure 12: Case 1 Repair Action



Notice that although demands increased sharply in 2003, procurement and repair actions ramp up slowly. This is again because the typical DoD requirements determination process uses a twenty four month rolling average as the basis for demand forecasting. This lagged average introduces a substantial delay in the process and, when combined with a twenty four month production lead time, creates a situation where inventories are rapidly pulled down following a sustained surge in demand and inventory recovery is very slow.

Case 2: Investment made to improve reliability, 33% improvement in reliability, and no increase in unit part cost.

Case 3: Investment made to improve reliability, 33% improvement in reliability, and a 15% increase in unit part cost.

Cases 2 & 3 examine the impacts of investments in reliability on demands, inventories, readiness, and life-cycle costs relative to the Base Case. Figures 13 – 15 present the results of these cases. It should be noted that although Case 3 involves a percent increase in unit part cost after the investment period, inventory levels, procurement actions, and repair actions are the same in both cases because it is assumed that funding is available to make the recommended buys and overhauls. The increase in cost of the part does, however, impact total life-cycle cost and reduces the return in

Case 3. Figure 13 presents simulation results for inventories for Cases 2 and 3. As may be seen, with the more reliable part entering service in 2006, inventories recover faster because of the improved reliability and reduced demands. In fact, because of the long production lead time and demand averaging, orders continue to be made at a higher than necessary level and inventories overshoot the objective before falling back to the steady goal appropriate for the new reduced demand levels. The unserviceable inventory level also rises because fewer parts require repair action due to improved reliability and reduced demand. Figure 14 shows a reduction in orders for new spares (the green tick marks are buys). Following the introduction of the improved part, the interval between orders increases because the parts are now more reliable and monthly removals are reduced. Lastly, Figure 15 shows a ramp up in unserviceable inventory after the investment period for Cases 2 and 3. As stated above, the improvement in reliability causes the unserviceable inventory level to rise due to reduced repair actions because of longer lasting parts. Thus, unserviceable inventory will build as fewer parts are overhauled. This may be seen in the lower levels of repair activity.

Figure 13: Cases 2 & 3 Inventory Levels

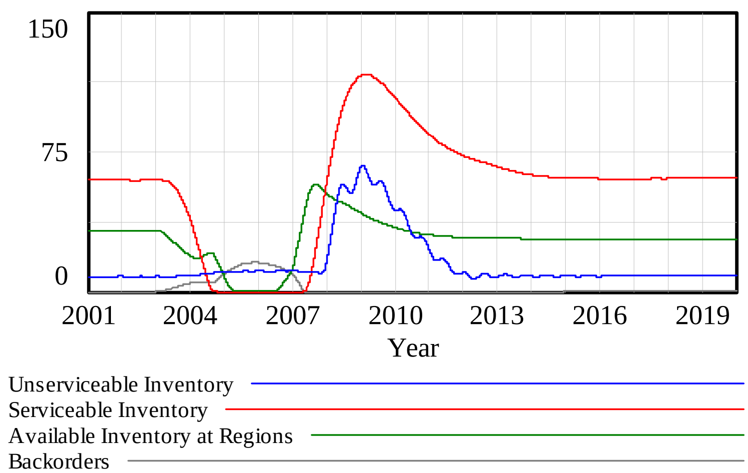


Figure 14: Cases 2 & 3 Procurement Action

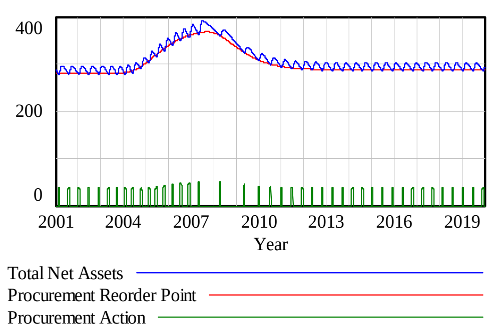
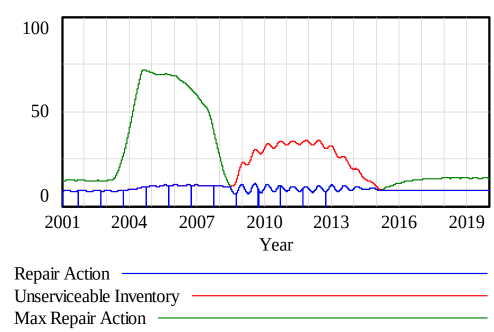


Figure 15: Cases 2 & 3 Repair Action



Case 4: Investment made to improve reliability, 50% improvement in reliability, and no increase in unit part cost.

Case 5: Investment made to improve reliability, 50% improvement in reliability, and a 15% increase in unit part cost.

Cases 4 and 5 were conducted to assess the impacts of even greater improvements in reliability. Figures 16, 17 and 18 present the results for Cases 4 and 5. Figure 16 shows that a 50% improvement in reliability greatly increases the sharpness and rapidity of inventory recovery. Also, the total number of backorders is lower than in any other cases. Figure 17 shows that in this simulation, once the investment period ends, the new improved parts are shipped in 2006 and 2007 at close to historical levels. However, since parts are lasting longer, fewer new parts are required to meet the requirements objective (RO). As a result, procurement actions are less frequent from 2008 to 2013. They then settle to a lower level that reflects the lower monthly demands. Similarly, Figure 18 shows that after the investment period, repair actions slow for one year again because of reduced demand arising from increased reliability in parts and then repair actions become somewhat less stable as the system adjusts to the new demand levels. Also, unserviceable inventory rises higher than any of the previous cases because less repair activity is required.

Figure 16: Cases 4 & 5 Inventory Levels

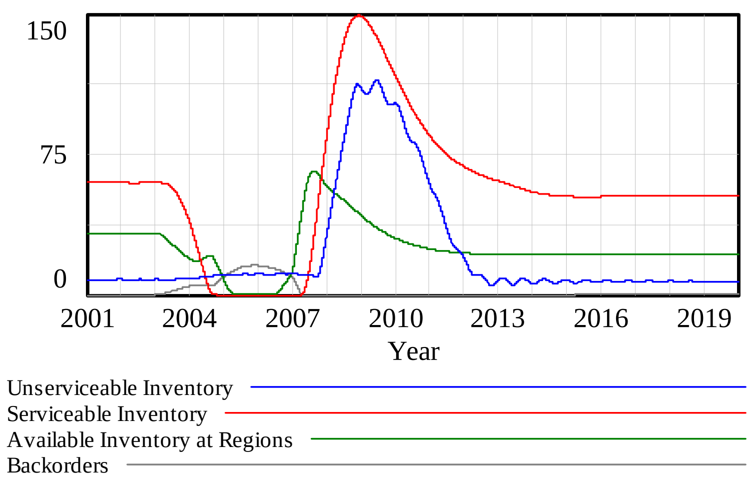


Figure 17: Cases 4 & 5 Procurement Action

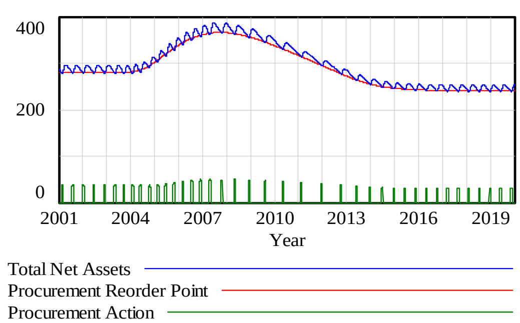


Figure 18: Cases 4 & 5 Repair Action

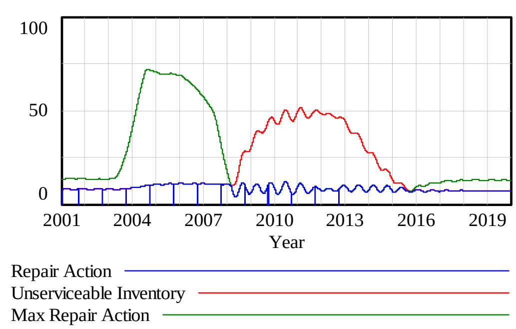


Figure 19 presents the current dollars (inflated dollars) annual spend on parts over the course of the simulation for all five cases. After the investment period, all cases show significant savings in annual spending relative to the Base Case 1. Case 5 shows an annual savings of $60 million for this single part in 2020. Figure 20 presents the current dollars cumulative spend over the ten year period of the simulation. For Case 5, the cumulative savings are roughly $600 million over this life-cycle assessment. Clearly, the greater the reliability improvement, the greater the total cost savings and these savings are significant.

FIGURE 19: Current Dollars Annual Spend Cases for Improved Reliability

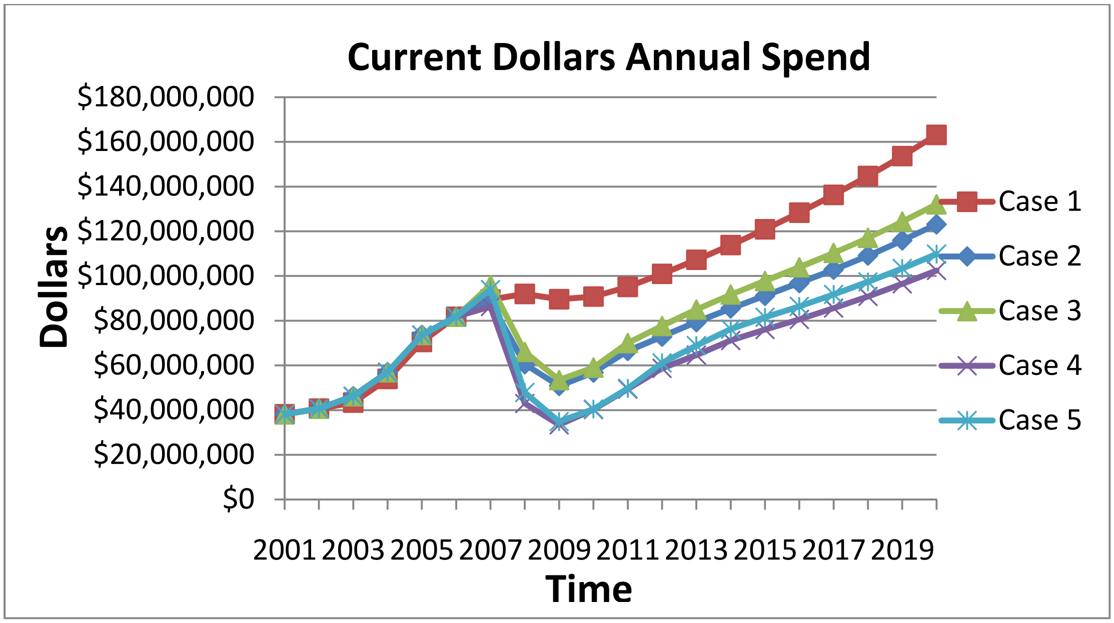


FIGURE 20: Current Dollars Cumulative Spend Cases for Improved Reliability

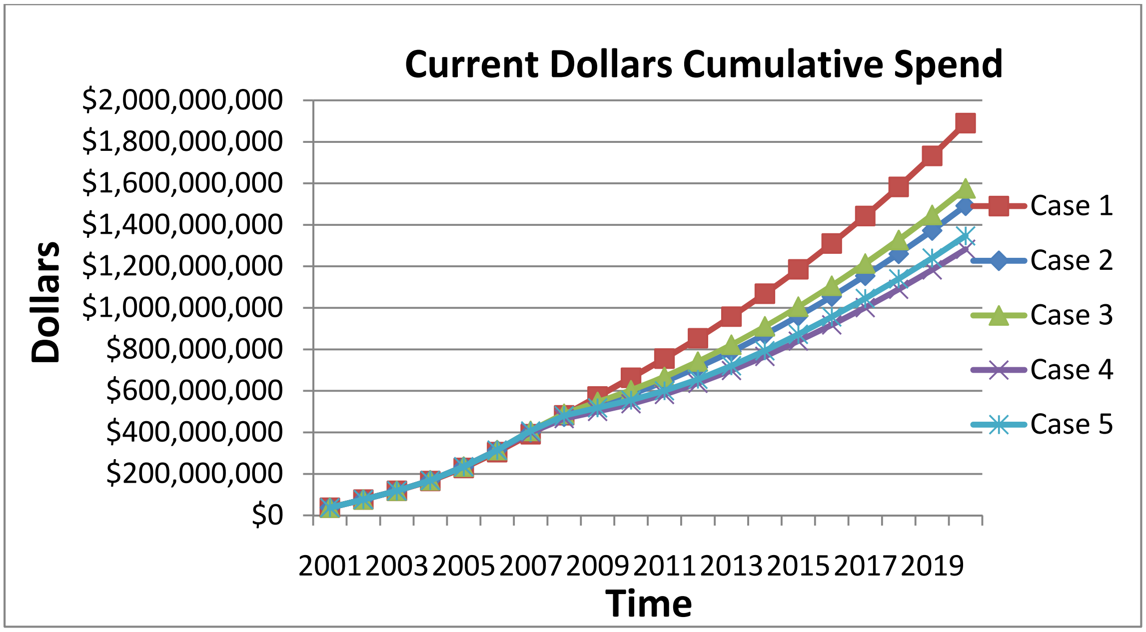


Figure 21 presents current dollars annual spending amounts for all five cases. For Cases 2 through 5, the "Savings" columns present the reduction in spending from Case 1 over the twenty year period. The yellow shading denotes the years in which an investment is made for improved reliability. The table also provides the payback or break-even (B/E) point in number of years. The lower portion of the chart presents the payback ratio for the investment. This final financial metric is obtained by dividing the current dollars cumulative savings by the total investment. The payback ratio demonstrates the time significance of the cost reduction for process improvement. For example, the results from Case 2 illustrate current dollars cumulative savings of roughly $75 million in the six years (2006 through the end of 2011) following the investment period. The chart indicates that a $3 million dollar investment spread equally over years 2003, 2004 and 2005 would be recaptured in 2.27 years after the investment period ends. A $6 million dollar investment spread equally over those same years would allow for a payback period of 2.66 years. To evaluate the alternative cases with different investment amount and payback periods, investment amounts of $3 million, $6 million, $9 million, and $12 million were used. Similarly, Cases 3, 4, and 5 also exhibit quick payback or break-even time in years. These results indicate the strong potential for reduced O&S costs through reliability investments.

FIGURE 21: Annual Spending & Savings for Cases with Improved Reliability

Current Dollar Annual Spending and Savings
Base Scrap/Loss Rate 35%, 15%
(% Improvement in Reliability, % Parts Cost Increase)
*** All Cost in Millions**

	Case 1	**Case 2**		**Case 3**		**Case 4**		**Case 5**	
Year	(0%,0%)	(33%,0%)	Savings	(33%,15%)	Savings	(50%,0%)	Savings	(50%,15%)	Savings
2001	$38.14	$38.14	$0.00	$38.14	$0.00	$38.14	$0.00	$38.14	$0.00
2002	$40.64	$40.64	$0.00	$40.64	$0.00	$40.64	$0.00	$40.64	$0.00
2003	$43.37	$43.37	$0.00	$43.37	$0.00	$43.37	$0.00	$43.37	$0.00
2004	$53.93	$53.93	$0.00	$53.93	$0.00	$53.93	$0.00	$53.93	$0.00
2005	$70.47	$70.47	$0.00	$70.47	$0.00	$70.47	$0.00	$70.47	$0.00
2006	$81.79	$81.79	$0.00	$81.79	$0.00	$81.79	$0.00	$81.79	$0.00
2007	$89.49	$88.60	$0.89	$96.28	-$6.79	$88.15	$1.34	$95.79	-$6.30
2008	$92.00	$84.23	$7.77	$91.23	$0.77	$77.36	$14.64	$83.95	$8.05
2009	$89.61	$71.92	$17.69	$77.37	$12.24	$62.84	$26.77	$67.47	$22.14
2010	$90.79	$68.14	$22.65	$72.64	$18.15	$57.35	$33.44	$60.65	$30.14
2011	$95.14	$67.49	$27.65	$71.60	$23.54	$53.33	$41.81	$55.92	$39.22
2012	$100.10	$68.23	$31.87	$72.18	$27.92	$51.13	$48.97	$53.27	$46.83
2013	$107.26	$72.91	$34.35	$77.01	$30.25	$55.26	$52.00	$57.39	$49.87
2014	$113.85	$80.41	$33.44	$85.18	$28.67	$63.11	$50.74	$66.02	$47.83
2015	$120.88	$87.46	$33.42	$93.20	$27.68	$71.85	$49.03	$75.95	$44.93
2016	$128.33	$94.38	$33.95	$101.01	$27.32	$77.45	$50.88	$82.61	$45.72
2017	$136.29	$101.83	$34.46	$109.16	$27.13	$84.23	$52.06	$90.15	$46.14
2018	$144.73	$108.92	$35.81	$116.83	$27.90	$90.47	$54.26	$96.93	$47.80
2019	$153.65	$115.94	$37.71	$124.37	$29.28	$96.44	$57.21	$103.36	$50.29
2020	$163.15	$123.11	$40.04	$132.07	$31.08	$102.48	$60.67	$109.83	$53.32
Cumulative Savings			$391.70		$305.14		$593.82		$525.98
Investment (over 3 year period: Years 2004-2006)									
$3 Million	B/E (years)		2.27		3.74		2.11		3.06
$6 Million	B/E (years)		2.66		3.98		2.32		3.19
$9 Million	B/E (years)		3.02		4.15		2.52		3.33
$12 Million	B/E (years)		3.19		4.32		2.73		3.46
Benefit/Investment Ratio									
$3 Million			129.57		100.71		196.94		174.33
$6 Million			64.28		49.86		97.97		86.66
$9 Million			42.52		32.90		64.98		57.44
$12 Million			31.64		24.43		48.49		42.83

Evaluation of Reliability Investment from Empirical Data

In the second part of the investigation, the model structure was again parameterized for a major repairable helicopter part but rather than for a variable demand rate, a twenty year steady state life-cycle was assumed. Moreover, this part of the analysis utilizes an empirical relationship between reliability investment and reliability improvement.

As discussed in the Introduction, LMI with the sponsorship of DoD developed a linear regression equation relating investments to reliability improvements. This linear regression is presented in Figure 1. The regression relates the Investment divided by the Average Production Unit Cost (APUC) to the Reliability Improvement Ratio, which is the percentage increase in reliability. By utilizing this linear regression, the likely improvement in reliability arising from a certain investment can be determined. It should be noted that in Figure 1 the cases in the lower range of the investment ratio tend to be for large systems or aircraft. As a result, ratios of 1 to 10 may not be appropriate for major repairable parts. Rather, ratios ranging from 20 to 1,000 may be more appropriate for investments to improve the reliability of major assemblies and parts. It is this upper range of investment ratios that is used in this study.

Table 2 presents four cases developed using the empirical regression between investment and reliability improvement.

TABLE 2: Cases for Improved Reliability Using Empirical Data

Case	Investment/ APUC	% Increase in MTBF	Reduction in Failure Rate Per Flight Hour
6	0	0	0.0%
7	20	150%	60.0%
8	30	200%	66.7%
9	40	225%	69.2%

For this part of the analysis, Case 6 represents the Base Case before any investment in reliability improvement is made. It represents “business as usual.” The “Investment/APUC” column gives for each case the ratio for investment to average production unit cost (APUC). For example, in Case 7 with an APUC of $250,000, an investment of $5 million yields an investment ratio of 20. For Case 8, an investment of $7.5 Million yields a ratio of 30 and for Case 9 an investment of $10 Million yields a ratio of 40. In the simulation analyses, the total investment amount is divided equally over three years (Years 1 through 3 of the simulation). The “% Increase in MTBF” column is calculated from the Linear Regression Example provided in Figure 1. The final column provides the reduction in failure rate per flight hour from the base failure rate. The Failures per Flight Hour is inversely related to the MTBF.

Figures 22 – 24 present the inventory levels, procurement actions, and repair actions over the course of the twenty year simulation for Case 6, the twenty year Base Case.

With constant demands, all inventory levels, and procurement and repair actions remain constant over the simulation as would be expected.

FIGURE 22: Case 6 Inventory Levels

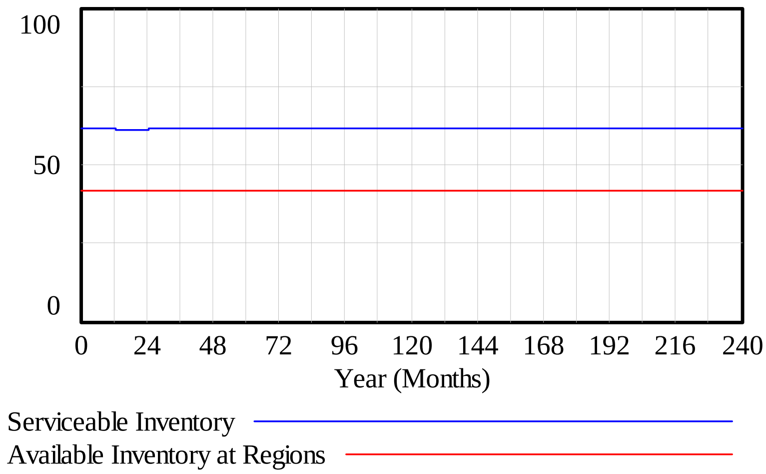


FIGURE 23: Case 6 Procurement Action

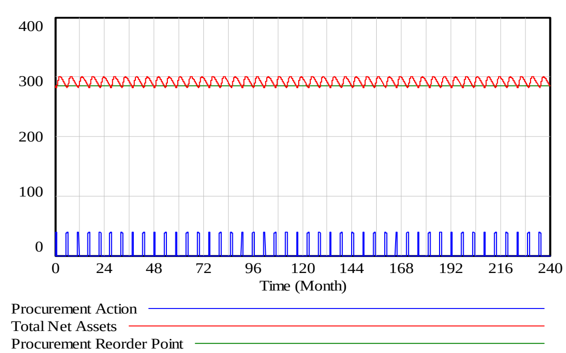
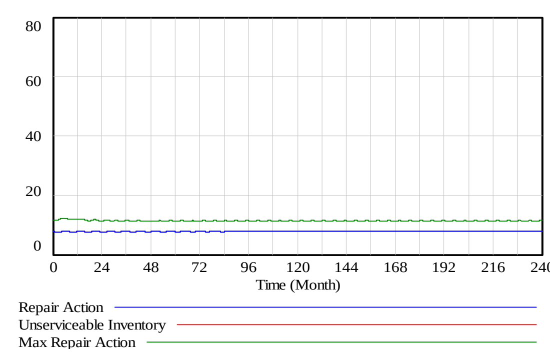


FIGURE 24: Case 6 Repair Action



Figures 25 – 27 present the results for Case 7 with reliability improvement of 150%. Note that these cases include large improvements in reliability. For Case 7, the MTBF is increased by 150%. This results in monthly removals dropping by more than half, in fact, a reduction of 60% over the introduction period of roughly eight years. As seen in Figure 25, inventory levels climb after the investment period (Years 1 to 3) and the new part begins introduction. The growth in inventory is a result of parts arriving out of a two year production pipeline into an environment of reduced demand. The model incorporates and simulates the actions of the requirements determination process which uses a twenty four month rolling average for demand. As a result, recommended procurement and repair actions do not begin to slow down in the simulation until over a year of reduced demands. Figure 26 presents procurement actions. Importantly, six years after the introduction of the new improved part, new procurement halts for three years so as to work off the accumulated inventory. Even as new procurement action begins to pick up, fewer numbers of new parts are ordered than initial levels. Figure 27 shows the slow reduction in repair action and the buildup of the unserviceable inventory.

This growth arises because fewer parts are inducted into the overhaul process due to longer lasting parts and reduced demands.

FIGURE 25: Case 7 Inventory Levels

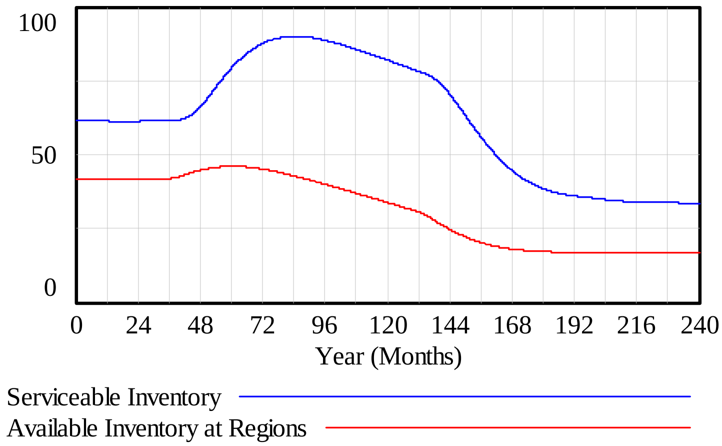


FIGURE 26: Case 7 Procurement Action

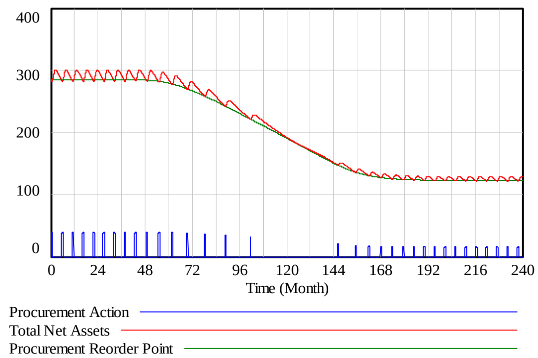
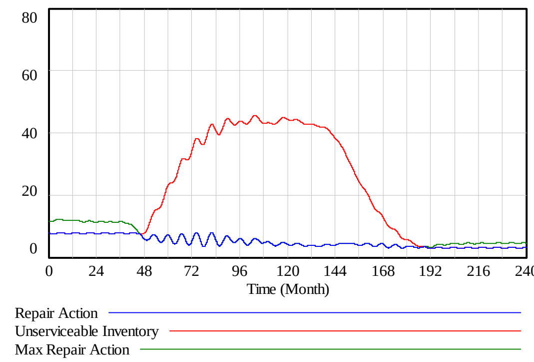


FIGURE 27: Case 7 Repair Action



Figures 28 – 30 present the results for Case 8, assuming a 200% improvement in reliability. Figure 28 illustrates the inventory levels, which, similarly to Case 7, become significantly higher following the investment period. Again, this is the result of reduced demands and historical orders emerging from the production pipeline. As parts become more reliable and last longer, serviceable inventories, unserviceable inventories, and available inventories at the regional facilities increase substantially. Figure 29 presents the procurement action over time. The orders for new parts halt for five years as the demand is consistently met through inventories and overhaul. Lastly, as shown in Figure 30, repair orders are reduced over time and that it requires a number of years to reduce the buildup of unserviceable inventory.

FIGURE 28: Case 8 Inventory Levels

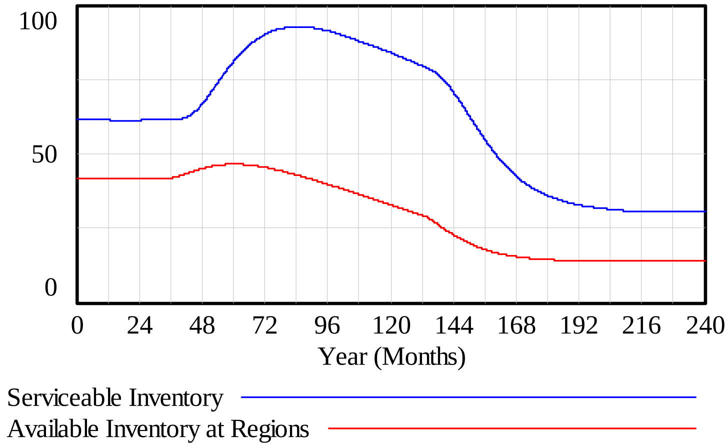


FIGURE 29: Case 8 Procurement Action

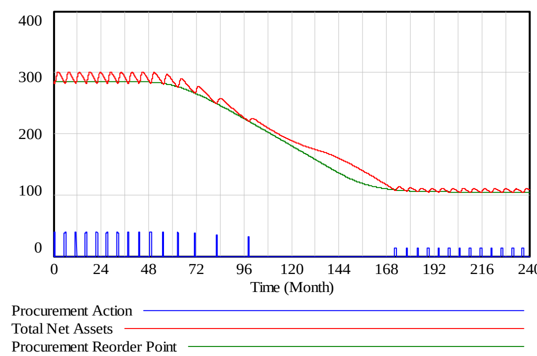
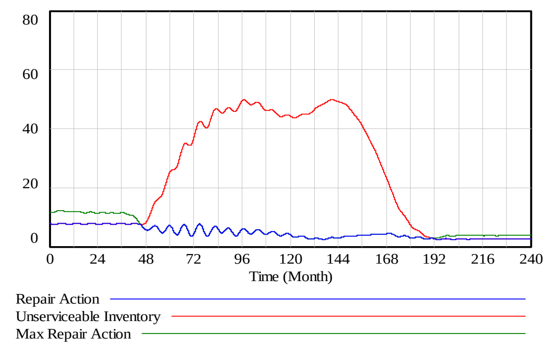


FIGURE 30: Case 8 Repair Action



Figures 31 – 33 present the results for Case 9 with a 225% improvement in reliability. Results are similar except that the buildup of inventories is greater and procurement is halted for a more extended period of time.

FIGURE 31: Case 9 Inventory Levels

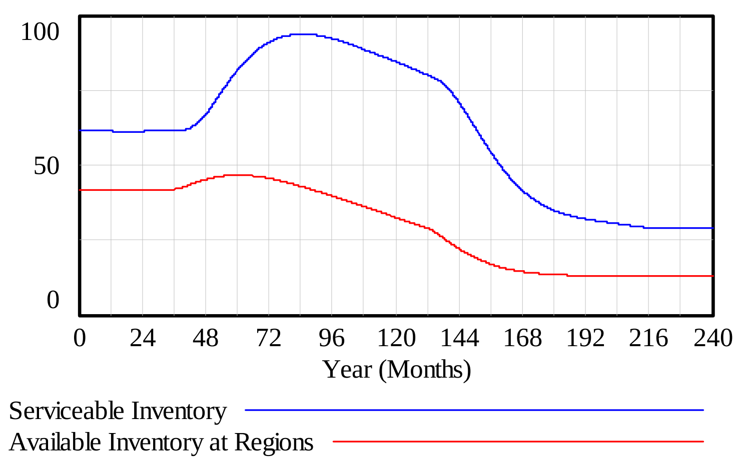


FIGURE 32: Case 9 Procurement Action

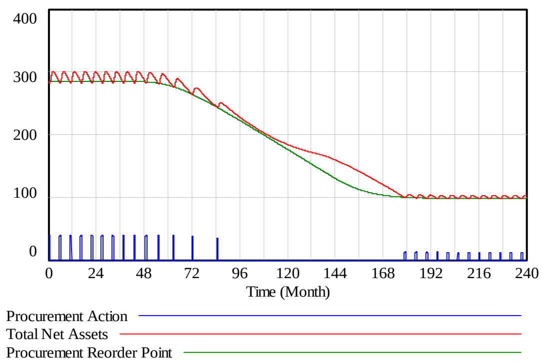


FIGURE 33: Case 9 Repair Action

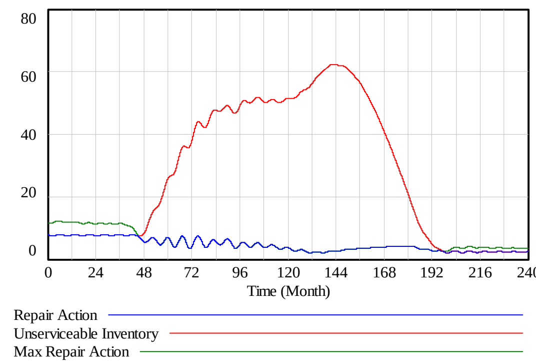


Figure 34 presents the annual spend in current dollars for the four cases. The investment expenditures during years one through three are included in the spend for Cases 7, 8 and 9. Note that the spend for the improved reliability cases drops significantly in the years following the introduction of the new part. This drop is associated with the sharp reductions in new procurement that occurs several years following introduction. When procurement begins to be required again, the spend begins a slow climb. In all cases however, the annual spend is roughly $60 million lower than the base cost in Case 6.

FIGURE 34: Comparing Current Dollar Annual Spend for Various Cases

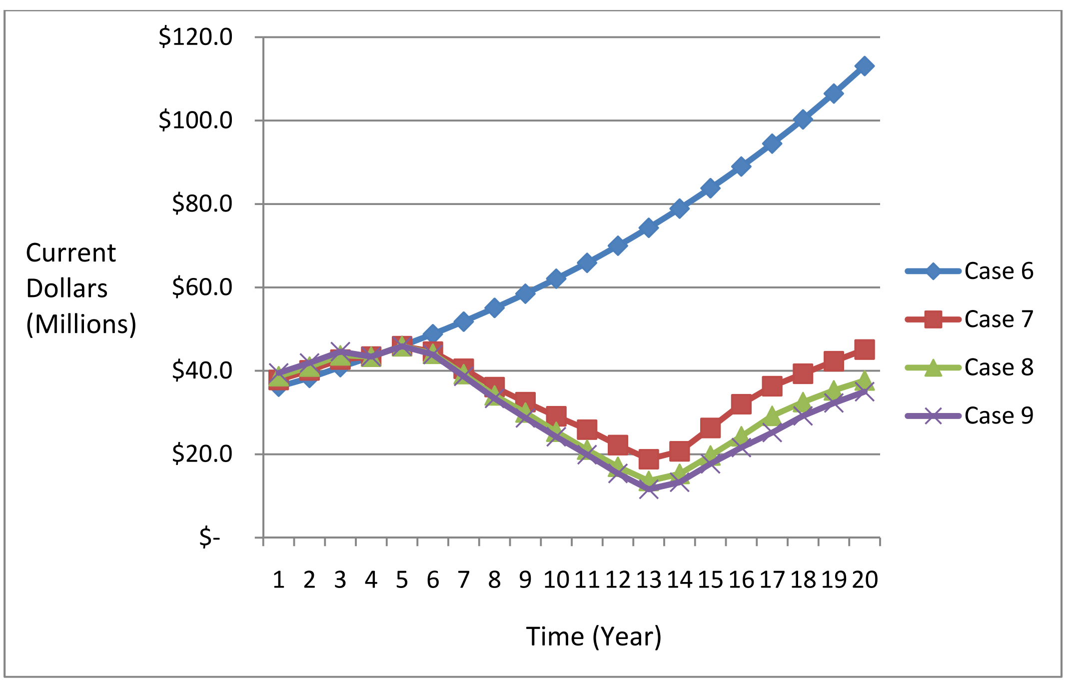


Figure 35 presents cumulative spend in current dollars for the four cases. The reduction in spending from the base over the twenty year life cycle ranges from $700 million to $800 million, thus, demonstrating the substantial returns provided by the investments that ranged from $5 million to $10 million for a part costing $250,000.

FIGURE 35: Comparing Current Dollar Cumulative Spend for Various Cases

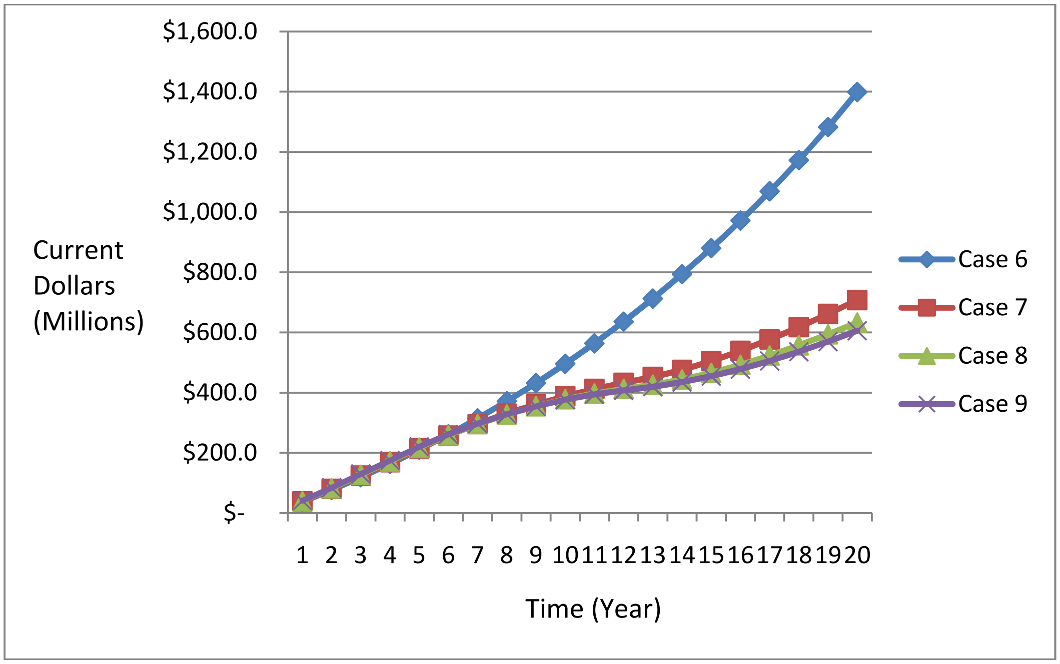


Table 3 and Figure 36 present a cumulative lifecycle summary for Cases 6, 7, 8, and 9. As may be seen, paybacks from investment in reliability can be very substantial and very attractive. Note that the investment amount is included in the costs of the alternatives. As Figure 36 illustrates, there is a point where the percentage in cost reduction begins to level off and decline. Savings reach an upper limit of approximately 50% of base costs and then decline as the investment amount increases and ultimately increases the total costs. Nevertheless, for the part with APUC of $250,000, investments in improved reliability on the order of $7.5 to $10 million generate estimated life cycle cost reductions of roughly $600 million in current dollars; this may be interpreted approximately as needing to buy 1,300 fewer parts over the 20 year life cycle.

Table 3: Reductions in Life Cycle Costs

Case	Investment	Investment/ APUC	Reliability Improvement %*	Cumulative Costs From Simulation (Current $)	Savings	Savings/ Base Cost
6	$ -	0	0%	$ 1,398,720,000	$ -	0
7	$ 5,000,000	20	150%	$ 707,848,000	$ 690,872,000	49.39%
8	$ 7,500,000	30	200%	$ 632,752,000	$ 765,968,000	54.76%
9	$ 10,000,000	40	225%	$ 605,767,000	$ 792,953,000	56.69%

As may be seen in Figure 36, there appears to be an investment “sweet spot” that exists in a range of (Inv/APUC) ratio between fifty and one hundred.

FIGURE 36: Constant Dollar Investment/APUC vs. Percent Reduction in Costs

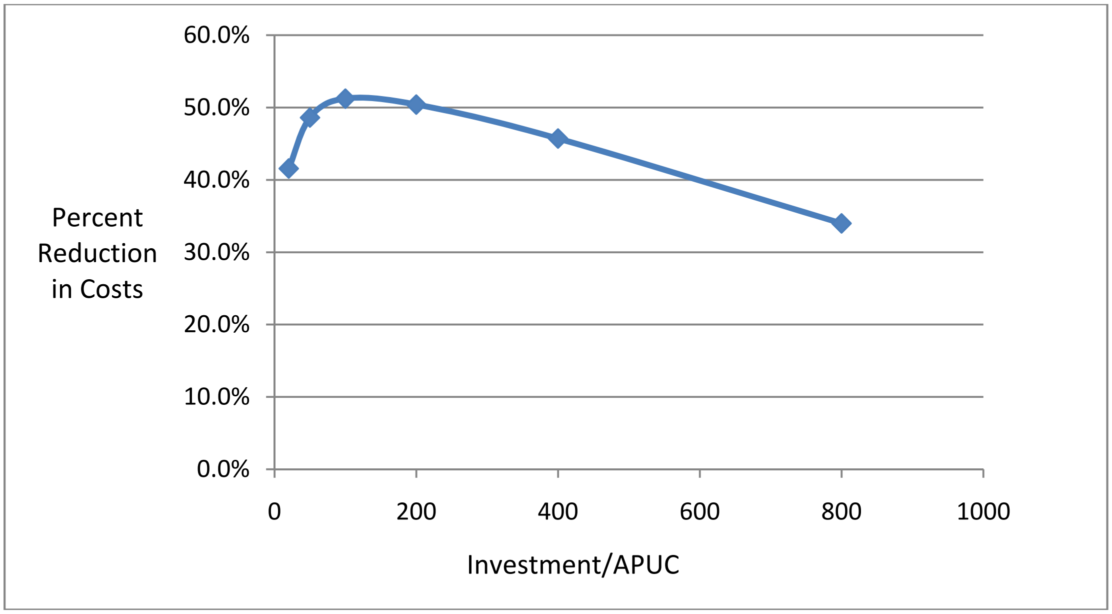
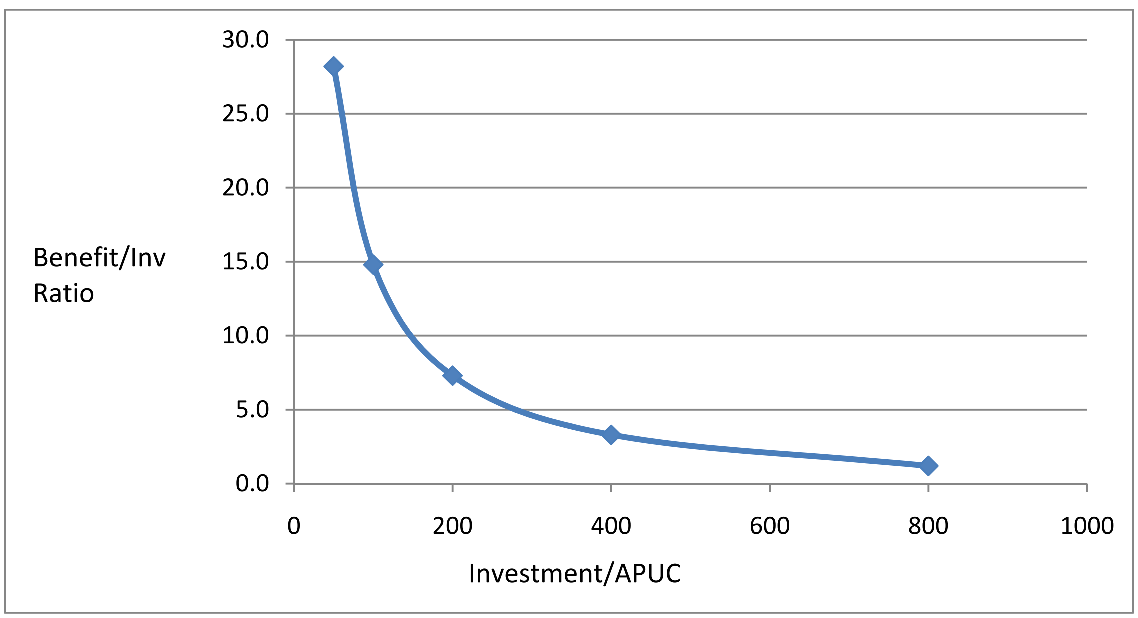


Figure 37 presents the Benefits (Savings) to Investment ratio as a function of the investment ratio in constant dollars. This reinforces the finding that an investment ratio exceeding 100 produces sharply lower returns.

FIGURE 37: Constant Dollar Investment/APUC vs. Return on Investment



Impacts on Readiness and Availability

Although the discussion so far has focused on economics, namely investments, costs, and savings, improvements in reliability can also have significant impacts on aircraft availability and readiness. Table 4 presents the impacts of improved reliability and failure rate reductions on aircraft availability and readiness. Failure rate reductions lower the average monthly removals and lead to increased annual aircraft availability hours. In this analysis, it is assumed a part in repair would ground a helicopter for three days (72 hours). The table presents the annual additional hours of availability that arise from the improvements in reliability assumed in Cases 6 – 9. As may be seen, the investments not only yield large savings in expenditures, but also provide thousands of additional hours of availability.

Table 4: Impacts on Aircraft Availability and Readiness

Case	% in Failure Rate Reduction (Failure Rate per Flight Hour)	Average Monthly Demands	Unavailable Hours per Year*	Unavailable Hours Reduction %	Annual Reduction in Aircraft Impacted	Annual Additional Available Hours
6	-	14.0	12,096	-	-	-
7	60.0%	7.4	6,394	47.1%	79	5,702
8	66.7%	6.7	5,757	52.4%	88	6,339
9	69.2%	6.4	5,519	54.4%	91	6,577

Sensitivity Analysis

A sensitivity analysis was performed to examine the impacts of monthly demand rates and average production unit cost (APUC) on savings and return on investment. In the sensitivity analysis, all cases assume a 150% improvement in reliability. From the empirical relationship in Figure 1, this means an Investment to APUC ratio of twenty. Thus for a part costing $250,000, the investment required is $5,000,000. For the part costing $500,000, the investment required is $10,000,000. As may be seen in Figure 38, the payback period in years (breakeven point) is achieved more quickly for a part with higher demands because of the greater savings for high volume parts. In addition, more expensive parts also exhibit faster paybacks than less expensive parts, again because of the greater savings. Figure 39 illustrates the cumulative savings for cases with higher demand rates and more expensive unit costs. Again, the greatest amount of cumulative savings is gained through helicopter parts with higher monthly demand and higher unit cost, as both variables directly impact cumulative savings over a system's useful life.

FIGURE 38: Payback Period with Varying Monthly Demands and Unit Costs

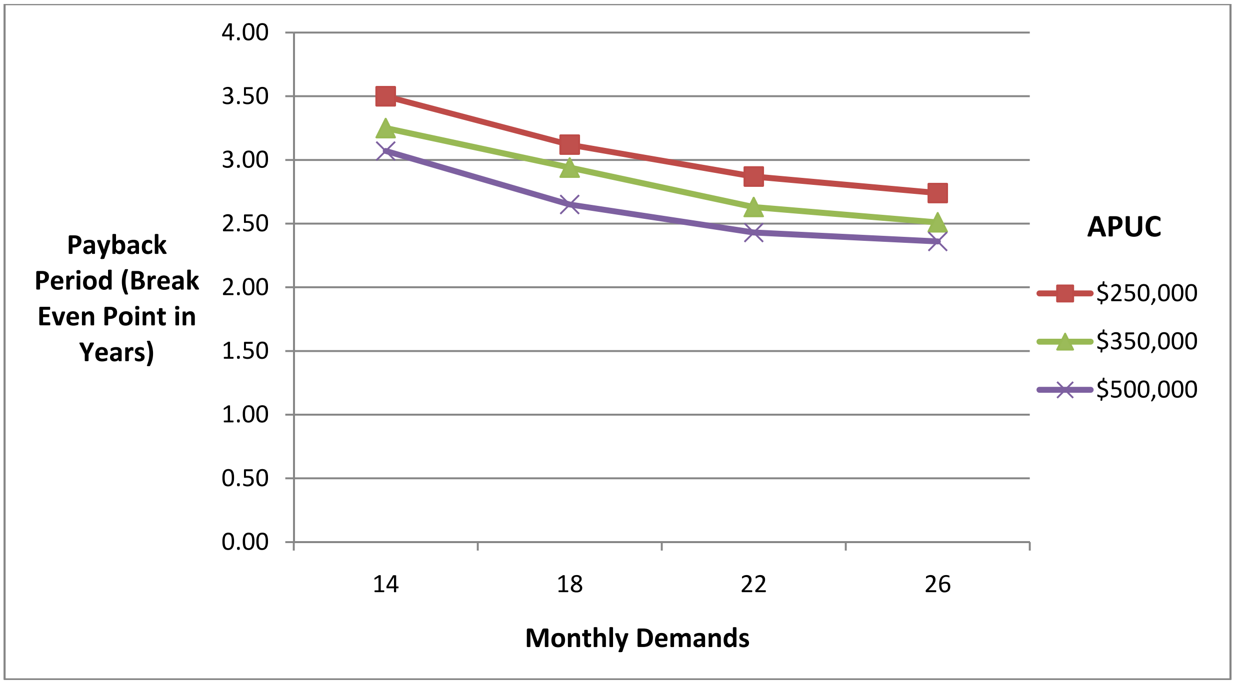
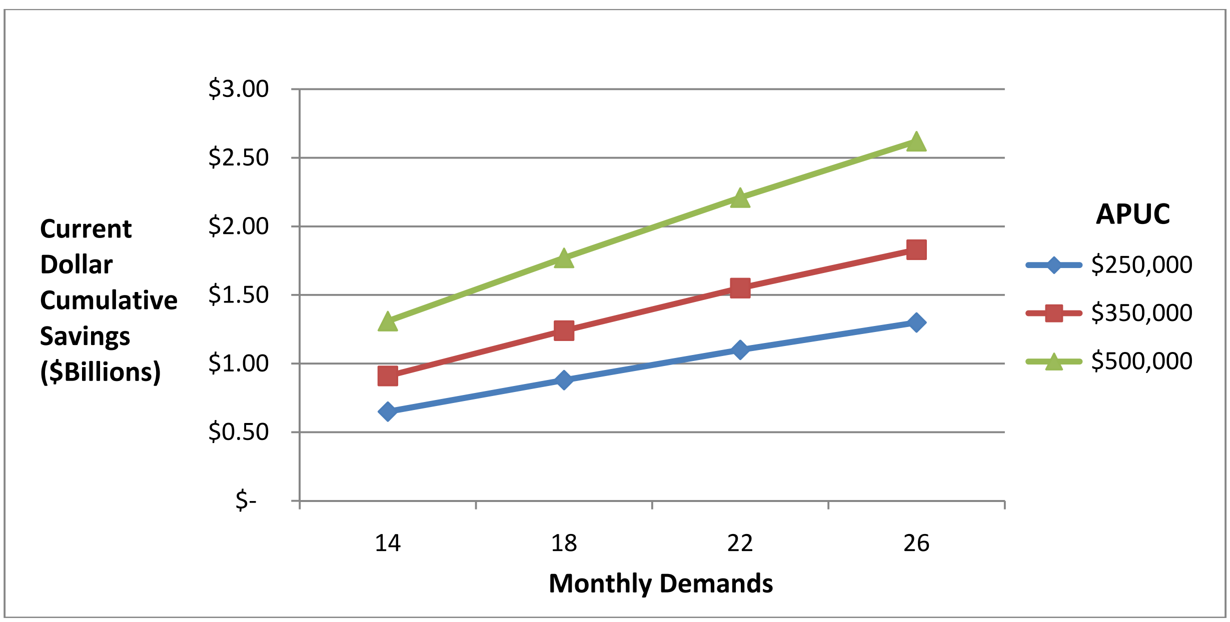


FIGURE 39: Cumulative Savings with Varying Demands and Unit Costs



Conclusions

“Doing more with less” has become a long-running and recurring theme across the globe. This challenge is especially acute for the US Department of Defense and the branches of the armed services where demands are great and budgets are tight. Because typically the costs to operate, maintain, and dispose of a weapon system account for about 72 percent of the total cost of ownership, much effort has focused on these expenditures. Long-term costs incurred in maintenance are subject to increased focus. Affordability is now a key metric. Improvements in reliability have multiple cost saving impacts such as fewer parts to buy and overhaul, smaller inventories of replacement parts, fewer inspections, reduced maintenance hours and down time, reduced transportation costs to ship replacement parts, and others. Because of the complexities of the supply chain and procurement processes, financial evaluation of reliability investment is very difficult. The requirements determination process, long production lead times, and target inventories must also be considered. A system dynamics model has been developed of an aviation supply chain that enables evaluation of alternative cases in which investments are made to improve reliability, lower total demands, and reduce spending on new procurement and overhaul over the lifecycle. It is shown that the payback potential of an investment depends upon annual demand for the part, cost of the part, percent improvement in reliability achieved, and any increase in cost of the part due to the re-design. The analysis show that returns can be high and payback periods can be fast, particularly for investments to improve reliability of items with high demand and high cost. Moreover, the simulation results indicate an investment “sweet spot” may exist in a range for the ratio of Investment/Product Cost between fifty and one hundred. In this range, the percentage reduction in cost is maximized. The research also indicates that close coordination is needed between program management, procurement planning and acquisition in order to fully realize savings. Ongoing research is developing reliability investment strategies and estimates for lifecycle costs under differing demand, manufacturing and overhaul scenarios.

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