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CLOSED-LOOP, SIMULATION-BASED, SYSTEMS ENGINEERING APPROACH TO LIFE CYCLE MANAGEMENT OF DEFENSE SYSTEMS

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ABSTRACT

Assessing the life-cycle impacts of operations and maintenance decisions made for new or aging systems requires an accurate ability to measure and respond to uncertainty. Maintenance and parts requirements forecasts for fielded military systems are traditionally performed through historical repair and supply demand models. These models work well once several years of steady state weapon system operation has been accomplished, but tend to depend on a stable and somewhat regular operations and support structure. Predictions based on data that capture the cyclic trends that tend to occur as the fleet endures standard operations, scheduled maintenance, and average component failure rates work best when components are relatively new. Aging systems comprised of component populations of varying ages can be adversely affected by change or the failure to change the traditional maintenance and support concepts. The right action for a new system may result in adverse impacts when considering older systems.

Further Explanation

A Closed-Loop, Simulation-Based, Systems Engineering approach to Life Cycle Analysis (LCA) provides a method for integrating the time dependent relationships of a systems reliability and operations to the maintenance, and supply support structure that must sustain it. Actions taken over time in any of these categories will somehow affect and impact the throughput and response time of the others. Simulation-based analysis offers the flexibility and expandability to model complex systems and their operations, maintenance and supply environments.

Clockwork Solutions is currently applying simulation based methods to develop LCA tools in order to aid the Department of Defense in its management of aging weapons systems. These tools are being used by the US Army, for example, to quantify time-dependent, life-cycle costs and impacts resulting from proposed aircraft and engine sustainment decisions, specifically, recapitalisation maintenance concepts. It provides a capability to assess decisions for the fleet prior to their implementation, enabling the US Army to achieve the best financial and readiness life cycle returns on their upgrade, acquisition and sustainment program investments.

Life Cycle Management (LCM) and LCA are a set of tools and techniques which are utilized by defense decision makers to base programmatic decisions on the anticipated mission-related and economic benefits derived over the life of a weapon system. This paper presents three alternate approaches to LCM and LCA, distinguished by both the granularity and the frequency of feedback between the elements being modeled. The merits and pitfalls of the different approaches are discussed and several examples of applying the approaches to defense LCM are presented, concluding with a case study of a project applying closed-loop simulation to answer key Life Cycle Management questions.

1 LIFE CYCLE MANAGEMENT AND LIFE CYCLE ANALYSIS CONCEPTS

1.1 Life Cycle Management and Life Cycle Analysis Defined

Life Cycle Management (LCM) is a management technique which bases programmatic decisions on the anticipated mission-related and economic benefits derived over the life of a weapon system. Knowing a system's life cycle characteristics and future behavior in advance enables decision makers to assess the cost-effectiveness of utilization, logistic support and engineering improvements scenarios before they are implemented. *Life Cycle Analysis* (LCA) is a formal process for establishing a quantitative basis in support of LCM decisions. LCA consists of: (i) building a model representation of a real world system or process, (ii) obtaining data to populate or instantiate the model, (iii) using the populated model to predict future behavior – e.g. performance and costs – for a range of defined system design or use scenarios, (iv) validating the model predictions, and (v) presenting the analysis results to decision makers.

1.2 LCA Applications to LCM

LCA can be used to support a range of LCM decisions during all stages of a system life. LCA provides program managers, item managers, and executive staff with rigorous quantitative support for strategic, tactical, and operational level decisions that previously had to be made based on crude approximations and intuition.

During acquisition LCA is used in support of investment decisions, including: identification of potential performance and cost weaknesses; assessment of alternative design options; and, evaluation of the cost and impact on system performance of alternative maintenance concepts.

During deployment LCA is used in support of change management, including: assessment of the effects of proposed engineering improvements on system performance and cost; changes in maintenance procedures and capacity; changes in supply practices to reflect component and system aging; and, determination of spare pool implications for technology refresh.

Finally, as an asset approaches its *end of life* LCA is used in support of transition management, including: support investment allocation among the systems to be retired and their replacements; projected remaining life of end-of-life extensions; and, assessment of required support resources.

2 A SYSTEMS PERSPECTIVE ON LIFE CYCLE ANALYSIS OF DEFENSE SYSTEMS

2.1 LCA Components – Cost and Performance Drivers

For the purpose of this discussion, we distinguish between the following major cost and performance drivers in the life cycle of a defense weapon system (Figure 1).

- Operations & Unit Maintenance – Those front line activities involved in flying/operating the weapon system (e.g. aircraft/tank) and performing first level maintenance work.
- Intermediate Maintenance – Performs intermediate level maintenance for weapon systems. Configuration and capabilities range depending on equipment, location, mission.
- Depot Maintenance – Performs range of maintenance from minor repair through complete overhaul of equipment not reparable by unit/intermediate maintenance, due either to policy or the requirements of the specific maintenance action. OEM (Original Equipment Manufacturer) maintenance also falls into this category.
- Management – Represents policy makers; management also balances requirements for support of multiple weapon systems.
- Engineering – Provide technical analysis and guidance leading to policy & procedures for items such as safety inspections.
- Supply/Logistics – Collective term for those activities which support the field and depot to ensure required spare parts are available when and where needed. In the U.S. Military, this function is typically performed both by DLA (Defense Logistics Agency) and the services themselves.

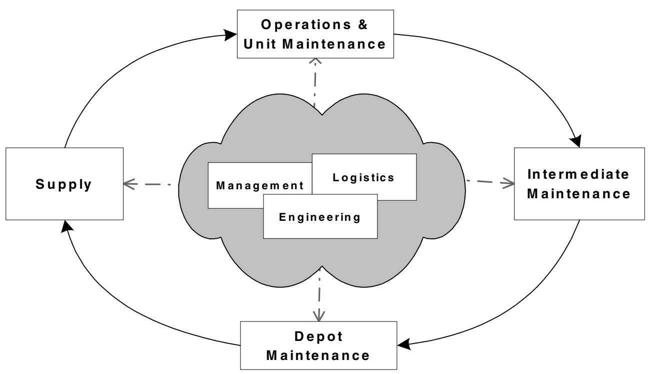

Figure 1: A Systems Perspective on Life Cycle Analysis of Defense Weapon Systems

Collectively, these elements form the *system* that LCA seeks to quantify and that LCM seeks to control and optimize. In this view, the system is broader than just the weapon system (i.e. hardware); encompassing all the operations, support, logistics, management, and engineering activities that occur throughout the life of the weapon system.

2.2 Segmented Life Cycle Analysis

Stemming from the complex nature of DoD systems as well as constraints in available models and computing power, traditional methods of LCA for DoD weapon systems have sought to segment the problem into palatable pieces. Within the DoD there are numerous LCA models – supply models, LORA (Level of Repair Analysis) models, RAMS (Reliability Availability and Maintainability) models, LCC (Life Cycle Cost) models, and models for determining maintenance staffing levels (Clockwork Designs 2000). Many times these analyses are performed by completely separate groups within the organization. Thus, for example, spare parts optimization is performed in isolation from maintenance resource level planning.

At first look, it seems reasonable to perform these analyses separately and then amalgamate the results to obtain a total view of the system's cost requirements and performance capabilities. To achieve this, *parametric interfaces* are specified by which factors/elements from one analysis or model are reflected as parameters in other analyses. For example, spare parts availability could be an *output parameter* from a spare parts optimization analysis and also an *input parameter* for a RAM model.

An example of a segmented life cycle analysis is given in Figure 4.

2.2.1 Problems with the Segmented LCA Approach

The problem with this approach is that the use of parametric interfaces between models implicitly assumes certain relationships between factors. There are indeed many strong relationships between factors (see Table 1), but the assumptions made about these relationships in order to parameterize models are not always adequate. For example, a constant failure rate is often computed from an FMECA and used as an input to an availability model. The problem with this assumption is that for many components, the failure rate increases over time, resulting in availability that decreases over time. Unless an aging distribution is assumed for the part, the availability analysis will be limited by the assumption of constant failure rate.

Table 1: A Few of the Relationships Between Life Cycle Components

Changing Factor	Effect of Factor Changing
Higher level of availability	Increases aging rates for components
Increased levels of spare parts	Increases availability
Higher level of availability	Increased flying hours means increased demand for spare parts
Higher level of availability	Increased load on maintenance system
More variable resupply times	Higher maintenance staffing levels are required to achieve same level of performance

These relationships are often too strong or too complex to be adequately captured by the parametric interfaces, particularly where there is feedback. The example of availability and reliability contains feedback, because at higher availability levels, parts will incur more time and thus their failure rate would increase more rapidly, which then affects availability, etc, etc.

It is important to note that a segmented analysis, under certain circumstances, can provide useful results for high-level quantification of systems behavior. This typically makes sense for a high-level prediction when less detail and more uncertainty in predictions are acceptable.

2.2.2 Segmented LCA Analysis Counter Example

A simple example was constructed to show the effects of feedback and parametric interfaces between analysis tools. A model was built that simulates a theoretical fleet of aircraft, each aircraft consisting of a single Line Replaceable Unit (LRU). The LRU has a failure distribution which causes "aircraft failure," events. When a failure occurs, the LRU is removed, and replaced with a spare if available. If a spare is not available, then this adversely impacts aircraft availability. The failed LRU enters a repair process. Figure 2 shows the elements in the model.

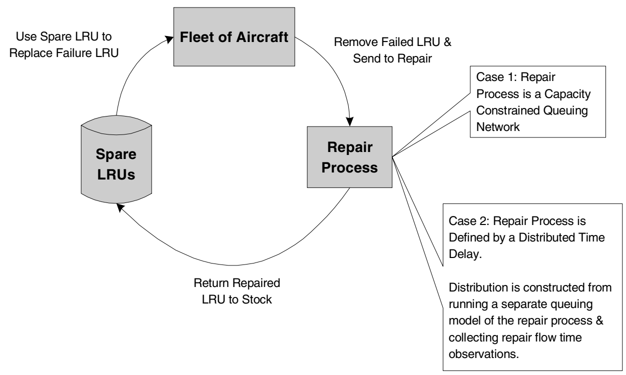

Figure 2: A Simple Model

Two alternate models of the repair process were employed. Case 1 treats the repair process as an explicit, capacity constrained queuing network. Case 2 seeks to replicate Case 1, by modeling the repair process as a black box in which LRUs dwell for a period of time governed by a distribution. This distribution was constructed from observed flow times (dwell times) in a separate queuing network model of the repair process.

In other words, in Case 2 the analyses has been *segmented* into a detailed repair model and an availability model. To someone not experienced in queuing models, this may seem reasonable at first look, since the distribution of flow times captures the variability and was constructed from an explicit model. Figure 3 shows how this assumption can have a significant effect on the predicted system performance – i.e. availability. It turns out that the more constrained the capacity of the repair process is, the larger the error in predicted availability for Case 2 will be.

2.3 Pseudo-Simulation Approach to Life Cycle Analysis

Another testament to the fact that these components are not independent and not easily segmented is the common practice in LCA of using one model to check and/or tweak the performance of another model. For example, the optimum spare parts allocation given by a sparing tool may predict a certain operational availability (Ao). Because of known

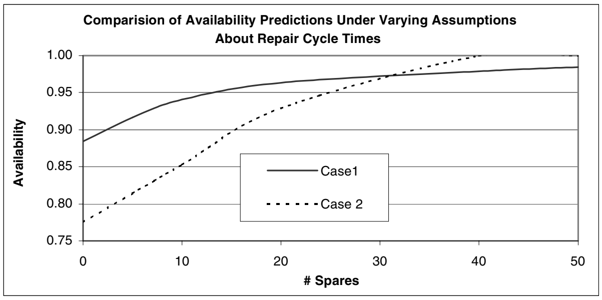

Figure 3: Availability Under Varying Repair Cycle Time Assumptions

weaknesses in the Ao predictions from the sparing tool, the operational availability is assessed by running the recommended sparing allocation through a RAM simulation. The sparing policy is then tweaked according to the simulation results and re-run through the RAM model in order to achieve the desired availability.

When this idea is taken to an extreme level, the feedback loop between otherwise independent analyses takes on the nature of what could be called a "pseudo-simulation." See Figure. The feedback loop could be never-ending since changes in one simulation affect the next, affects the first again, etc. The low bandwidth of the interfaces between segmented models means that it *may never be possible* to capture the right relationships between factors in the models.

2.4 Closed-Loop, Simulation-Based, Systems Engineering Approach To LCA

2.4.1 Description

In order to most accurately predict the future behavior of the aspects that comprise a complex DoD weapon system, the interdependencies among these aspects should be explicitly accounted for, just as they are inseparably and explicitly linked in the real world. A closed-loop simulation approach seeks to quantify the relationships of multiple system aspects in a *single integrated model* and thus overcome the problems that occur with utilizing parametric interfaces between multiple models.

In a closed-loop simulation, interface/feedback between system elements is explicit, fine-grained, and continuous. For Example, *every time* a demand for repair occurs, the model handles the demand by assigning resources, adding the element to a queue to wait, etc. Contrast this with the feedback between models in a pseudo-simulation; the level of granularity is much coarser, perhaps annually – i.e. repair demands *per year*. The frequency of utilizing the interface is up to the modeler, but may be once a day or more realistically once a quarter.

Robustness and hence confidence in predictions is enhanced by using modeling tools that impose few restrictions on the ability to describe the system, the attributes of its components and the *interactions among the components*. (Clockwork Designs 2001)

2.4.2 Other Advantages and Some Disadvantages of Closed-Loop Simulations

Several advantages exist for closed-loop simulation models, beyond those already discussed. Performing what-if scenarios requires the analyst to change only one model, rather than changing several models and then making sure they are consistent. Simulations accommodate sensitivity analyses to assess the impact of dirty data; therefore absence of "perfect data" is not a deal killer. Integrating data from multiple sources to create input data sets leads to better understanding of the data and allows continuous improvement of data collection and data systems.

Disadvantages of closed-loop simulation models are closely related to the advantages. To construct input data sets, data from multiple data systems must be gathered, scrubbed and integrated, which takes a non-trivial amount of time and effort, as well as coordination among different group and systems. This effort is handsomely rewarded in most cases by the robust analysis that follows, but recognizing this trade-off is a valid concern. Another disadvantage to closed-loop simulations is that the simulation execution time can be longer than that of traditional, non-simulation based analysis tools. It is important to recognize that if an analysis is going to result in large savings, then incurring a 5 hour run time is "down in the noise." This issue is becoming less important as computer processing speed increases and simulation technology improves.

3 CLOSED-LOOP LIFE CYCLE ANALYSIS CASE STUDY

3.1 Aviation Total Life-Cycle Analysis Software Tool - AT-LAST

Over the course of several years, starting with a project on behalf of the US Air Force and more recently for the US Army, Clockwork Solutions has developed a closed-loop simulation based Life Cycle Analysis tool in order to provide the robust life cycle analysis capability discussed above. The Aviation Total Life-Cycle Analysis Software Tool – (AT-LAST) has been developed to allow for stochastic, event driven, time dependent analysis of weapons systems in operation around the world. An example of closed loop life cycle analysis is given in Figure 6.

This model allows analysts to answer key LCM questions: "What will happen, when will it happen, and what will it cost us?" Questions / Answer scenarios supported by AT-LAST include, but are not limited to, the following:

- Will the fleet, or assets at some operating location, achieve required flying hour programs?

- Will my buy plan be suitable to maintain expected and target availability?
- What will my parts requirements be?
- How do improvements in repair capacity impact repair turn around time and time on wing?
- Where will my repair and supply bottlenecks be?
- What can I expect to have in the repair pipeline due to removals for cause and life-limited parts?
- What volume of part condemnations will occur and where?
- Will a repair location be able to keep up with the demands anticipated?
- What percent of time is repair held up due to awaiting parts or awaiting maintenance conditions?
- What performance gain (fleet availability, time on wing, repair turn around time) is obtained through selection of an alternate part type, with respect to

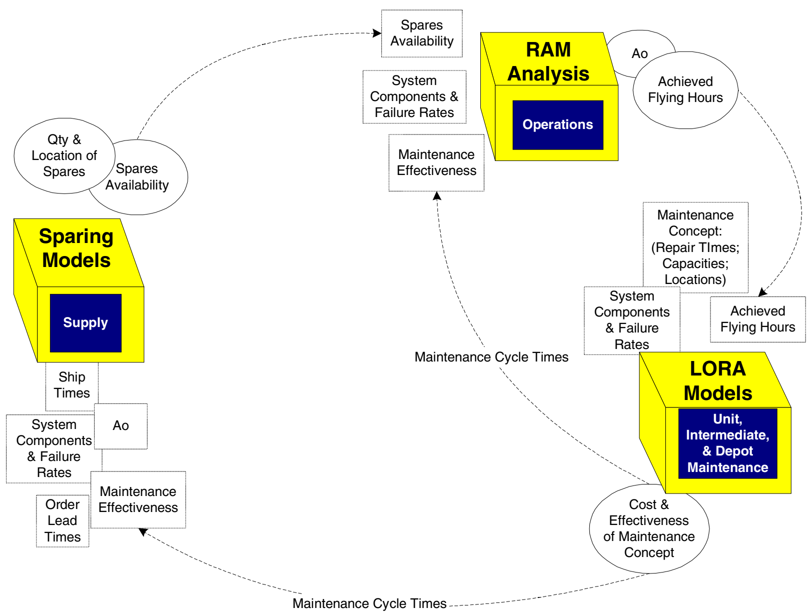

Figure 4: Segmented Life Cycle Analysis

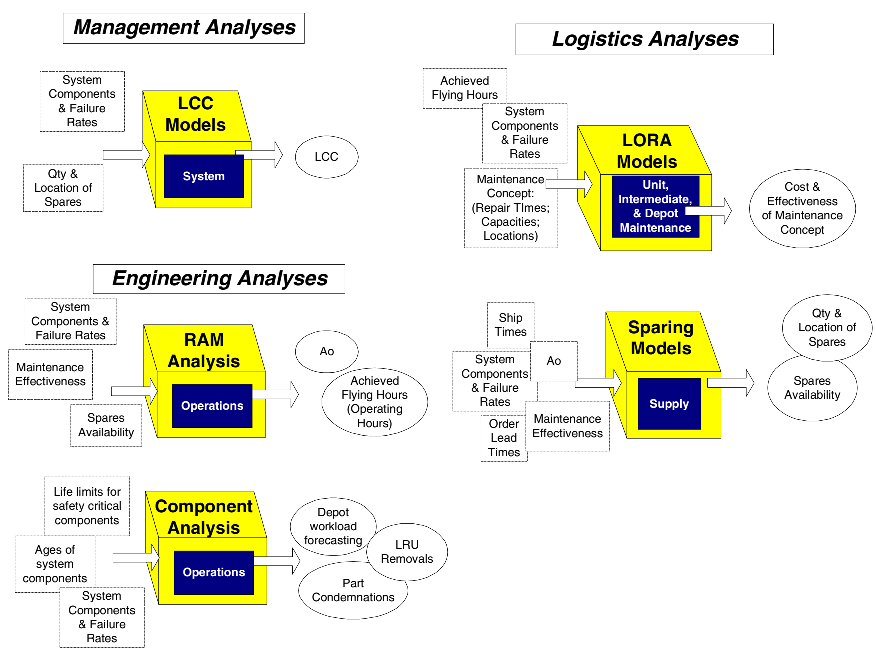

Figure 5: Pseudo-Simulation for Life Cycle Analysis

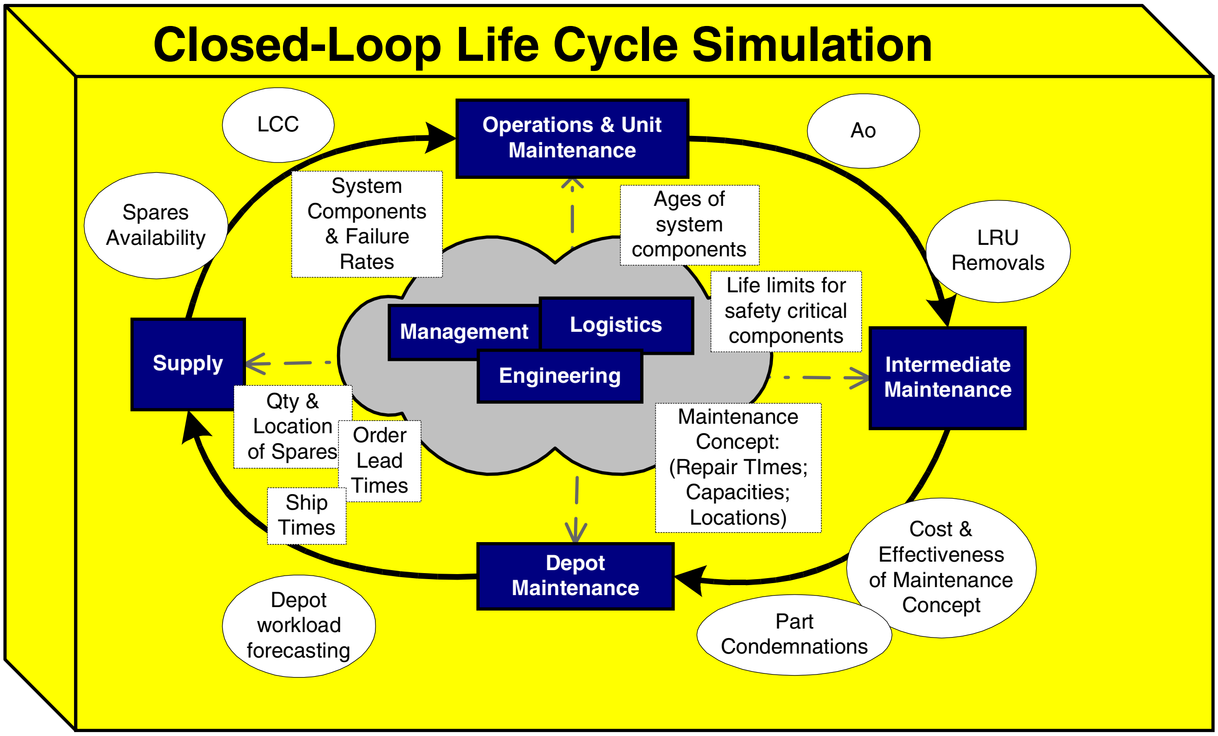

Figure 6: Closed-loop Life Cycle Analysis

- part and vendor attributes such as order lead-time, ship time, purchase cost, and reliability?
- If fatigue-testing results in modified life limits on certain parts, how will that change effect maintenance and supply volume?

3.2 Representative Case Study : Applying Closed-loop Simulation Models to Military Recapitalization Efforts

3.2.1 Recapitalization in Today's Military

"We need to replace aging aircraft and make our military more agile, to put our troops anywhere in the world quickly and safely. Our men and women in uniform deserve the best weapons, the best equipment, …"

- State of the Union Address by President George W. Bush, January 29, 2002.

Recapitalization (Recap) is the rebuild and selected upgrade of currently fielded systems to ensure operational readiness and/or "zero time, zero mile" systems. Recapitalization efforts are under way throughout the U.S. and other militaries. Decisions are being made to recapitalize assemblies based on their age, known degradation, and the resulting cost and benefit to the fleet as a whole. Predicting the overall impact to the fleet the recapitalization programs will have over time is a major technical challenge, especially due to the dynamic nature of uncertainty within operations, maintenance and overall support. Recapitalization of aging systems is a perfect application for closed-loop simulations because the effects of aging cause significant changes in the dynamics of all aspects of the weapon system's environment.

This case study presents a representative recapitalization analysis for a fleet of aircraft conducted with AT-LAST. (Clockwork Solutions 2002) The fleet was simulated for approximately 15 years of operation. The aircraft and several hundred thousand components are initialized with representative accumulated ages. The recap scheme implemented in this example is that when a DLR (Depot Level Reparable) arrives to the depot through the normal maintenance process, if it is on the list of recapitalized items, it will be overhauled and/or replaced with new components in order to restore the item to an as-new condition. There are many variations upon this scheme that can and will occur in the real world, such as scheduled inductions of aircraft for recap, scheduled induction of DLRs etc, and combinations of these schemes.

Figure 7 shows that as DLRs arrive at the depot and are recapitalized, O&S costs initially escalate because of the increased work scope for recap. As the recapitalized DLRs are cycled back into the fleet of operational aircraft, the costs begin to decrease due to increased reliability of components, and hence increased time on wing, decreased removals, etc.

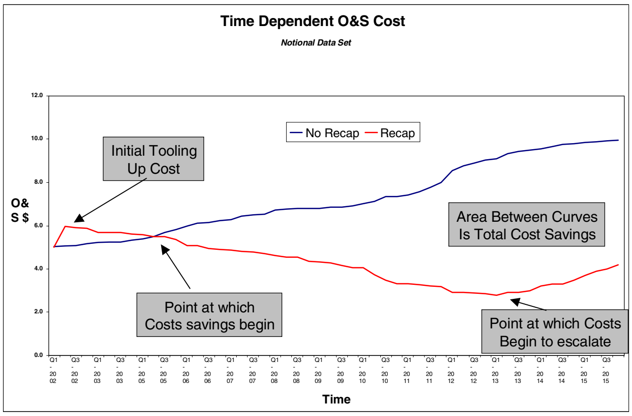

Figure 7: Time Dependent O&S Cost

Depending on the recap policy chosen, costs will eventually begin to climb for the same reasons as before (aging systems) – recap just postpones the current trends.

Similarly, fleet readiness and time on wing show significant & delayed benefits from recap, and eventually will follow the original aging induced trends. (Figure 8).

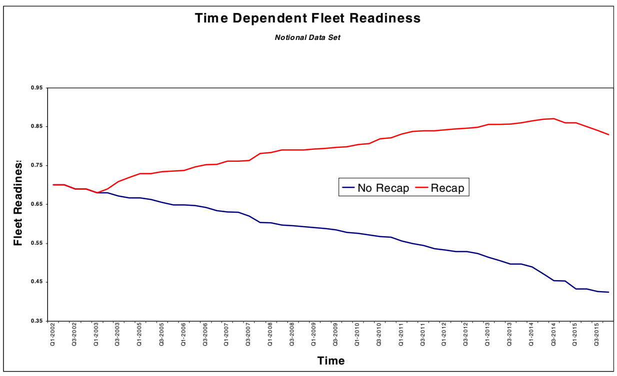

Figure 8: Time Dependent Fleet Readiness

Other Key Output Metrics Include:

- Performance, Reliability & Cost Metrics:
  - Average Time on Wing per DLR Over Time
  - Average Operational Time Accrued per DLR Over Time
  - Average O&S Costs per Flight Hour Over Time
  - Scheduled vs. Achieved Flying Hours
  - DLR and Sub-part Removal Counts
  - Condemnations per DLR
- Supply System Metrics:
  - Spares Levels over Time Per DLR
  - Logistics Response Time Per DLR
  - Spares Parts Availability Per DLR
- Average Time Spent Awaiting Parts (AWP) per DLR
- Maintenance Metrics:
  - Average Time Spent Awaiting Maintenance (AWM) per DLR
  - Depot Flow Time.

4 CONCLUSIONS

Life Cycle Management (LCM) is conducted by weapon system managers using quantitative Life Cycle Analysis (LCA) tools. The components of a weapon system's life cycle have many strong relationships which do not lend themselves to segmenting the problem into separate pieces in order to perform LCA. Closed-loop simulation models which integrate operation, maintenance, supply, and all other relevant factors into one model provide more accurate results than traditional segmented LCA models. Recapitalization of aging systems is a perfect application for closed-loop simulations because the effects of aging cause significant changes in the dynamics of all aspects of the weapon system's environment. However, these simulation techniques and tools can also be used to assess time dependent strategies and alternatives in maintenance induction, reliability improvement, system deployments, component wash out, maintenance capacity, supply chain management and system configuration modi-

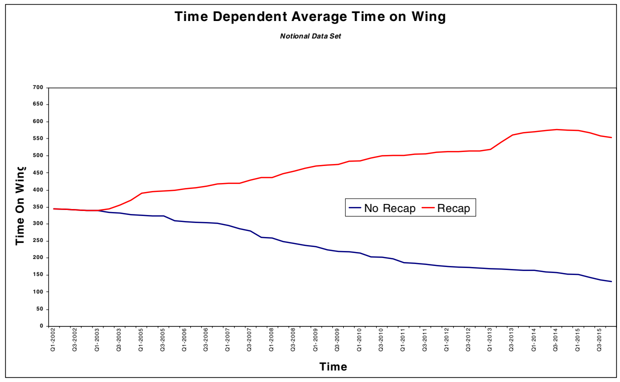

Figure 9: Time Dependent Average Time on Wing

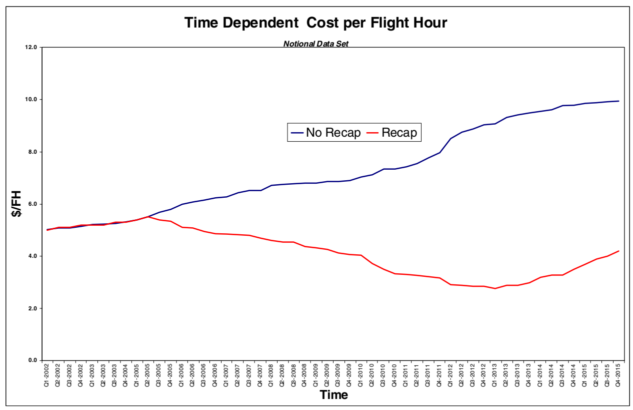

Figure 10: Time Dependent Cost per Flight Hour

fications. Successful strategies can then be measured in terms of their ability to improve operational (hours of operation, time on wing, maintenance demands), maintenance (cycle time, wait time, throughput) and supply (stock levels, wait time) metrics into the future. These forecasts can then help system managers assess the expected financial and readiness gains a system or series of systems will result in through the implementation of the proposed life cycle management strategies.

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