Maintenance Performance Modeling to Sustain System Operational Requirements for Complex Military Platforms

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Abstract

Both military and commercial asset management practices are receiving renewed scrutiny to reduce the logistic cost of ownership. Asset managers are being asked to analyse and improve on maintenance practices. This paper describes the application of computer modelling techniques to evaluate the effectiveness of existing and alternate maintenance solutions. Modelling using computer simulations is widely applied to new system development and allows complex processes and structures to be analysed and quantitatively evaluated. However, less work has been undertaken in applying modelling techniques to analyse existing in-service maintenance systems performance against potential alternatives.

Specific characteristics of a stochastic model for complex military platforms have been identified to assure that model implementation accurately represents suggested maintenance processes. Systems Engineering methodology is used to create and analyse targeted maintenance models in question: reactive and proactive variants. Existing maintenance process has been described and performance measurement criteria have been identified. In conclusion the models' effectiveness has been evaluated and complemented by its sensitivity analysis. The objective is to present the case study of maintenance modelling applied for the complex military platform.

Introduction

The 2007-08 Australian defence budgets were in total A$22 billion dollars, A$6.2 billion dollars of which was capital investment. Notwithstanding these record levels of investment, significant shortfalls for ongoing maintenance of assets, rising personnel costs and escalating research levels are expected (Thomson 2007). Defence Materiel Office (DMO) is seeking innovative ways of reducing the cost of ownership for new and existing assets while maintaining their operational capability.

For existing in-service systems, the sustainment process needs to be re-evaluated and optimised based on the collected data. Historically, the sustainment process evolves reactively to meet the changing platform system needs. Applying a Systems Engineering approach to change management, user needs must be analysed and implemented to provide "best fit" within the holistic set of objectives related to the system in question.

The importance of alternative maintenance concepts and policies has been realised in the late eighties, for example Nickerson (Nickerson 1990) discusses maintenance issues in the US Navy and a computer based solution approach for maintenance management. However, research activities and discussion of maintenance alternatives is still going on, for example paper (Funk 2005) presents an experiences based approach to maintenance within production systems. A resent publication (Sondalini 2010) presents condition based maintenance strategy for equipment failure prevention, it also points out that about 15% to 20% of equipment failures are age related, and the other 80% to 85% are totally time-random events. Paper (Durocher 2004) describes future control technologies in multi component motor diagnosis and system health monitoring and their impact on predictive and preventive maintenance practice. A generic mathematical model for a condition-based maintenance has been published in paper (Makis 1998). Publication (Amari 2006) describes a model of cost-effective condition-based maintenance using the Markov Decision Process with excellent introduction to the problem space.

Our paper discusses the applicability of computer modelling techniques to conduct case studies, sensitivity analysis and evaluation of the overall effectiveness of various maintenance solutions for existing military platforms, as a case study.

This paper presents maintenance policies modelling, describes the details of suggested variants of maintenance. The presented model and performance analysis produce information about the system characteristics before significant resources are committed for actual change in system operation and maintenance. In conclusion summary of models performance, observations and limitations is presented with suggestions for further research directions to be undertaken.

Maintenance of Complex Military Systems

The maintenance of a complex military system includes various activities: encompassing condition monitoring design attributes, inventory, Computer Maintenance Management System (CMMS) and personnel management. For military systems, criticality and safety are a significant attributes necessary to consider in handling system alarms or making resulting decisions of system maintenance and operation. Other unique features of really Complex Military Systems are (1) a relatively small number (dozens) of unique platforms included in the system and (2) the priority of platform availability for operation over maintenance cost savings. Most systems have a relatively limited time life span, which has to be carefully considered for statistical modelling with limited number of individual states.

All mentioned characteristics make model behaviour sensitive to initial conditions of platforms and an initial predefined maintenance schedule, typically used as a benchmark. Complex military systems failure analysis and modelling are not trivial or standard; usually failure of platform has a complex dependency upon the states of subsystems and comprising units, having individual failure rates distribution. Thus, accurate modelling of system (platforms) failures representing assumed dependencies is mandated to satisfy verification and validation requirements.

Due to the complexity of platforms, subsystems and units' states analysis, policy rules, application of the decision logic for maintenance acceptance and level of maintenance category is also not trivial and straightforward. Therefore accurate and correct modelling of different policies for maintenance decision making is required to find out the most appropriate and acceptable solution.

Maintenance System Characterisation

The maintenance system is characterised primarily by the equipment being maintained and its operational concept which is usually documented in a Technical Maintenance Plan (TMP) or similar artefact. The TMP outlines the maintenance policy, as determined during system and detailed design in support of system availability requirements and consistent with initial maintenance policy requirements. In our case concept of system operation includes pre-scheduled maintenance cycles for each platform referred to as Usage Upkeep Cycle as shown in **Figure 1** below, where each row represents two years of scheduled maintenance and boat operation cycles.

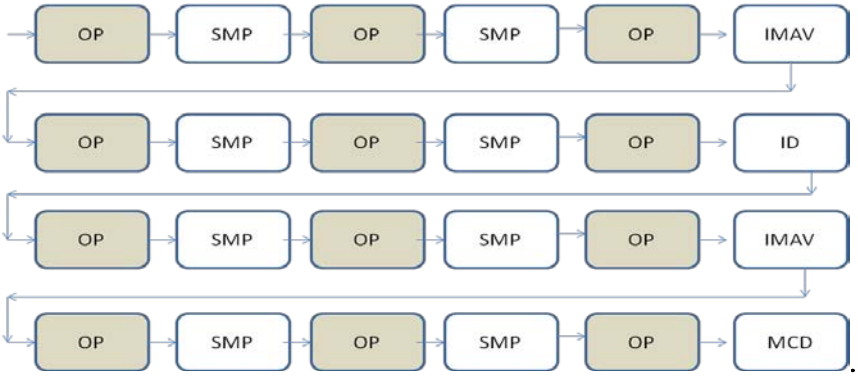

Figure 1 Platform Upkeep Cycle

Table 1 below is a legend of maintenance elements shown in Figure 1. Together these describe a schedule basis for the platform maintenance policy, based on the 96 month material certification cycle.

Table 1 Platform Upkeep Cycles

Upkeep Cycle	State code	Notes
Operational	OP	Mission Execution
Light Maintenance	SMP	Usually no units repairs or updates
One Year Maintenance	IMAV	Some subsystems repair
Two Years maintenance	ID	Most subsystems repair
Four Years Maintenance	MCD	Most subsystems repair and upgrade
Eight Years Maintenance	FCD	Complete boat renovation

Common types of employed maintenance policies are predictive and preventive. Predictive maintenance, including Condition Based Maintenance (CBM), is a maintenance policy that schedules maintenance based on system estimated performance and diagnosis information More recent systems use an embedded predictive maintenance policy variant, which integrates current performance, and operational and configuration parameters to schedule upgrades and maintenance as required. These systems rely on data representing component performance history, predictive diagnostics (prognostics) and system health management.

The policy described above contrasts with the more traditional cyclic maintenance variant (or preventive) adopted by many inservice military systems. Preventive maintenance is intended to prevent faults from occurring during its operational phase and is based on a concept of pre-planned periods for operation and pre-planned periods in which maintenance activities must be undertaken. That preventive approach with prescheduled regular maintenance works in other industries for complex systems, like, telecommunication networks. Equipment failure and expected degradation behaviour for most hardware technologies are time dependant and usually cyclic by nature. This factor affirms the value of cyclic maintenance. However, when extended periods of operational readiness are required, any compromises to cyclic maintenance schedules inevitably resulting in the deferral of maintenance. That sort of pre-scheduled maintenance violation can in some instances have an adverse impact on platform reliability.

Maintenance Modelling Approaches

Paper (Cho 1991) surveys the body of work between 1960 and 1989 associated with optimal maintenance and replacement models for multi-unit systems. The survey categorised each model relating it to a maintenance policy or replenishment plan. For all categories the models are based on the stochastic nature of equipment failure rates but tend to be applied to parts of a system or process rather than representing the whole system. That approach fits most of modelled commercial applications with massive number of customers or components. The survey refers to many examples of stochastic failure modes feeding queues representing repair venues and its capacities. In each case models are implemented through multi state Markov chains and are aimed at optimising maintenance and replacement. These models are generally limited to single component systems with a simple maintenance policy.

Agent-based modelling is a more recent approach to modelling complex system behaviour. Its popularity is aided by advances in computing power and has been further fuelled by an increasingly complex world cross influences and relations. Paper (Macal, 2005) states that agent-based modelling is suited to complex real world systems such as Command and Control and supply chains. It follows that an agent-based model would provide an accurate and effective representation of a complex military platform maintenance system. Strictly speaking we used agent based approach for software model design to achieve model flexibility to handle required maintenance policy implementations, however, still using standard reliability stochastic approach for platforms failure modelling.

Maintenance Model Description

This section briefly describes the maintenance system under consideration and details model criteria required to achieve the model outcomes. The complex military platform maintenance system described in this paper services six platforms (submarines) within a 10 year cycle. The issues under scrutiny are those ones that directly attribute to the management or decision process of the maintenance. These are shown in figure below.

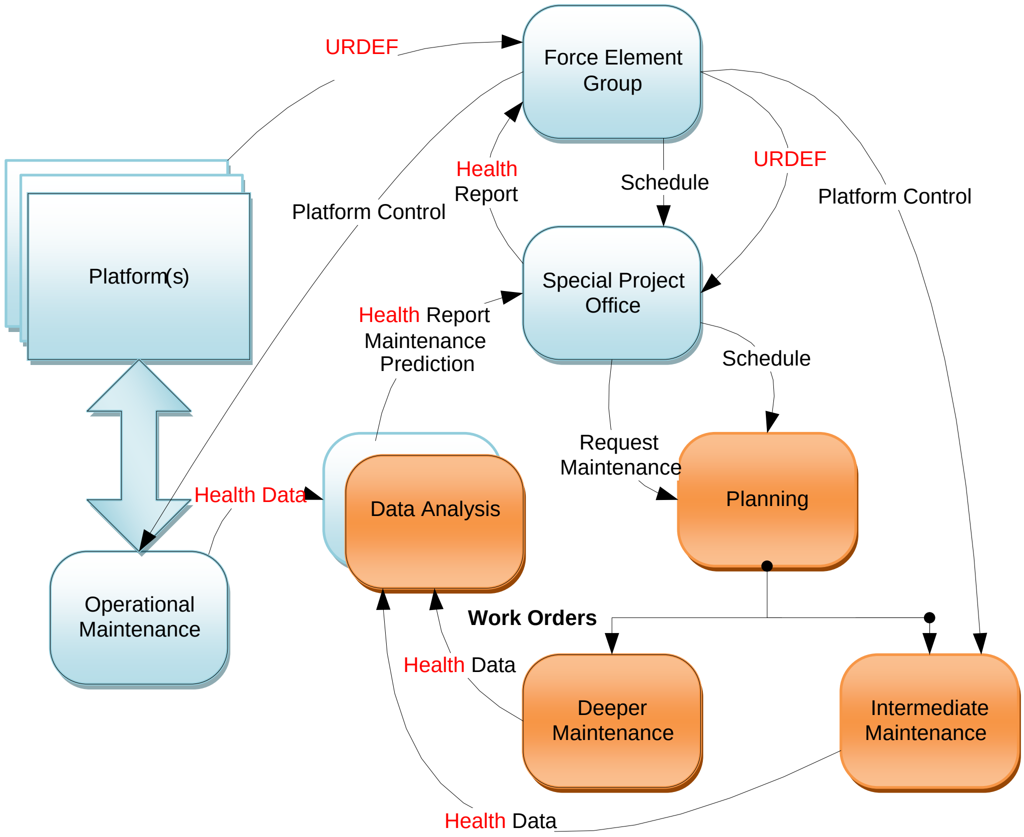

Figure 2 Maintenance Management Model

Additional logistics support functions supporting the maintenance system, including training stores and repair loops embedded into the planning and maintenance processes, are not discussed here. The model identifies two main triggers that generate unscheduled maintenance. These are Defects and Health Report (Diagnosis) events. When reported, defects generate three levels of response:

1. Priority 1 – Defect or condition that precludes the platform remaining at sea or completing a mission.
2. Priority 2 – Defect or condition that limits the platform's ability to complete a mission but requires rectification at the first opportunity.
3. Priority 3 - Defect or condition that does not inhibit the platform's activities and can be fixed at the next suitable opportunity.

In addition to defects reporting, operational level maintenance inspections and data collection is undertaken, providing raw health data for further analysis. The data analysis function compares this data with known historical data to develop a system health prognosis. This is used to schedule remedial maintenance and/or to defer scheduled maintenance.

Stakeholders determine operational and maintenance schedules in consideration of:

- Manning;
- Endurance;
- Cost;

- Tasking;
- Certification; and
- Operational readiness.

The Measures of Effectiveness (MOEs) for this platform agreed with the stakeholders and can be defined as:

- Average Number of Sea Days available for missions per platform per year.
- Probability of having more then certain threshold number of platforms available for operation

These provide guidelines for statistics collection and measurement basis for a maintenance model.

Maintenance Model Design

Figure 2 illustrates a simplified graphical model of the maintenance system management. Much of the process is defined by maintenance policy identified earlier that dictates the basis on which decisions are made and the rules for making them. As is typical for socioeconomic systems, these rules are not strictly based on yes/no type of questions. They depend on many distantly related factors such as the amount of leave due to the crew as a basis of whether to schedule the repair of a failed subsystem. While these extreme elements will not be considered, it does highlight a need for maximum flexibility in applying rules to manage interaction between model entities. For this reason an agent based software implementation has been chosen to allow flexibility in modelling system behaviour and maintenance policy. In our paper we do not distinguish who optimises maintenance policy and decisions: human or software expert system. Paper (Jardine 2002) discusses benefits and disadvantages of Expert System application for optimising condition based maintenance decisions.

To successfully evaluate a particular maintenance policy, its results need to be compared with absolute quantifiable expectations against a benchmark predefined maintenance schedule and other required maintenance policies. To achieve the valid comparison, model fidelity is paramount to guarantee results credibility.

Two significant maintenance scenarios for modelling comprise:

1. Reactive: where subsystems are run to failure; and
2. Proactive: where subsystems are maintained through preventive maintenance routines, inspections and replacement in advance, before hardware failure.

In the Reactive Maintenance Scenario (RMS) subsystem failure is an accepted event and subsystems are run to failure. Once failed, the unit is repaired at the next maintenance availability with appropriate schedule adjustments. RMS is characterised by minimal or no control of the scheduling of maintenance events.

The Proactive Maintenance Scenario (PMS) incorporates inspections and preventive maintenance to predict and/or minimise failure and to schedule corrective or preventive maintenance before the failure event can occur. In the proactive maintenance scenario maintenance is scheduled based on subsystem health data.

Regardless of the maintenance scenario, each is based on a set of rules and decision logic guiding maintenance conduct and the way each subsystem health event should be handled. Table 2 Model Logic presents the logic conditions and its meaning used for each model type.

Table 2 Model Logic Conditions

Logic conditions	Reactive	Pro-Active
Subsystem health status	Exponential distribution based on subsystem failure rate and usage	Exponential distribution based on subsystem failure rate and usage
Health Monitoring Status	Health degrades to a failed condition. It is checked daily during operational periods.	Health data is visible for monitoring after a predefined percentage of the mean failure period.
Scheduled Condition Monitoring	No	Weekly as specified
Scheduled Refurbishment	As specified	No
Unscheduled Preventive Maintenance	No	As Specified
Subsystem Health Assessment (Urgent, Routine, Minor)	Yes	Yes
On Failure - Immediate Repair for	Urgent Failures	NA
On Failure - Schedule Repair for	Routine and Minor	NA
On Detection -Immediate Repair for	NA	No
On Detection - Schedule Repair for	NA	Urgent, Routine, Minor

The main element failure rates and conditions being modelled are the Platform, Subsystems and Units. Each platform comprises many subsystems and each subsystem may have multiple units. For example a pump subsystem may comprise two individual pumps that provide redundancy for that system. Platforms, subsystems and units are defined as follows. Figure 3 illustrates the system reliability model for a platform. Each platform Pj comprises a number of pubsystems Pj = {S1, …S25} working in sequence. And each subsystem Si includes a number of identical units Si = {U1, …Um}, working in parallel and where $m \geq 1$.

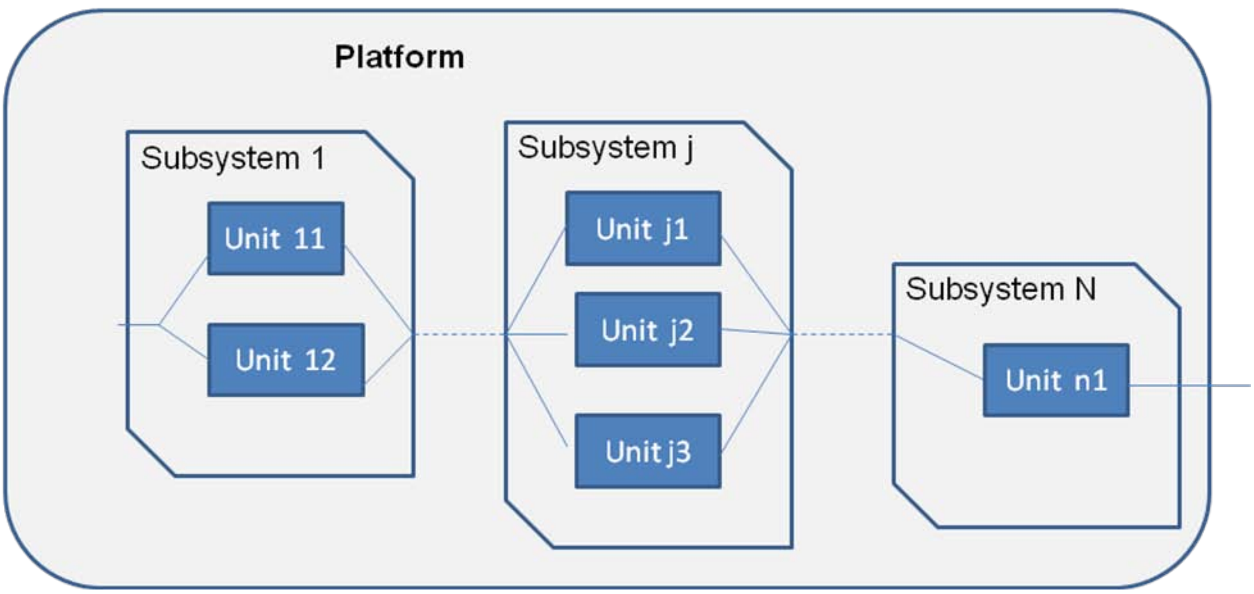

Figure 3 Reliability model for a platform system

This Platform element represents a collection of Subsystems and Units as described above.

The Platform agent reports:

- Its health based on the health of its Subsystems,
- Its age within the context of the model timeframe, and
- Its status in terms of whether it is operational or under maintenance.

The platform agent function evaluates the health of each of its subsystems and based on a hazard assessment of the subsystems, determines and reports its health. At the end of a maintenance period the platform health state is reset based on maintenance conducted and outstanding unit failures. If subsystem Si has failed then platform Pj will be flagged as failed.

The platform agent comprises a pre-defined number of instances of unique Subsystems, each of which comprises at least one unit. The failure rate of each unit is a stochastic value calculated from the exponential distribution.

Subsystems comprising only one unit are considered to have failed if its unit fails. For subsystems comprising multiple units then subsystem failure is determined based on the failure of a predefined number of units out of the total available units. This accounts for redundancy in subsystems and is predefined in terms of k out of n units remaining operational.

The failure predicted time allocated to each unit is calculated on initialisation and each time that unit is repaired. If sufficient units in a subsystem Si have failed then Si is flagged as failed. Each subsystem agent is characterised by state variables:

1. Health,
2. Subsystem Redundancy (K out of n subsystems),
3. Time to Repair,
4. Failure Rate,
5. Failure criticality,
6. Minimum Maintenance Period, and
7. Refurbishment maintenance period,

Each unit will be in one of three states: operational, failed or under maintenance. When the life of a unit exceeds the operational lifetime value defined by the simulation clock then the unit changes its state to *failed*. Unit agents are characterised by state variables: life span, and its failure status.

The Usage Upkeep Cycle briefly described in **Table 1** defines a 10 year maintenance cycle as a plan of scheduled maintenance activities. This plan is applied to each platform but needs to be initially populated for each platform by matching maintenance schedule. Therefore all platforms are not in maintenance concurrently. Three factors dictate this:

- Original submarine operational deployment schedule (one submarine per year)
- Limitations on manpower and facilities at maintenance faculties
- Strategic need to support a given number of platforms in an operational state at any time.

When the platform has no failures and is not in maintenance then its state is “Operational”. If it does have a recorded catastrophic failure and it is not in maintenance then it is in an “unknown” state and will transition to a maintenance state when maintenance is scheduled for it.

A normal operation state sequence comprises transition from “Operational” to one of the scheduled maintenance states and then returns to “Operational” at the end of that maintenance period.

A catastrophic failure renders the platform unserviceable (not safe for “Operation”). In this case the state is changed to “Unknown” until maintenance can be scheduled. This state change is necessary to distinguish that the Platform is no longer “Operational” regardless of the logic related to maintenance scheduling.

The “AdHoc” state is used to rectify priority 1 failures to return the platform to operational. This is undertaken based on the results of decision logic applied in each instance. Platform state transition is predicated on the health status and decision logic.

The operational state of the platform is determined by its Health state and decision logic. A Health state is applied to both the Platform and Subsystem and is transitioned when Unit failure is detected or when maintenance is conducted.

Figure 3. Health State Diagram, illustrates the health states reflecting the defect levels discussed earlier.

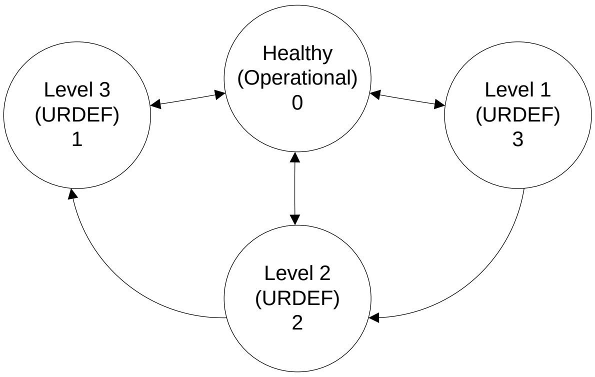

Figure 3. Health State Diagram

Maintenance Policy (Decision algorithms)

Decision algorithms shape agent behaviour based on the platform maintenance system processes. Individual subsystem maintenance policy is defined as part of the input parameters. Significant decision rules that need to be reflected in the logic are:

1. If a Subsystem has (K => N) Unit failures then the Subsystem health = the failure level defined for that subsystem.
2. If a Subsystem has (1 <= K < N) Unit failures then the Subsystem health = Level 3 failure.
3. A Level 3 failure requires immediate attention..
4. A Level 2 failure requires scheduling at next opportunity.
5. A Level 1 failure can be repaired within the subsystems normal maintenance schedule.

6. A Level 3 failure will cause the Platform to revert from “Operational” to “Unknown” state.
7. A level 2 failure will not alter the operational state of the platform.
8. A level 1 failure will not alter the operational state of a platform.
9. For a Level 3 failure the Model will schedule an AdHoc maintenance period to occur immediately.
10. AdHoc maintenance to repair Level 3 failures creates a 14 day plus MTTR reduction in the Operational Period.
11. Other maintenance may also be combined in an AdHoc maintenance period if required.
12. Condition Monitoring occurs as a preventive inspection scheduled at a predefined periodicity.
13. When Unit deterioration is detected, maintenance will be scheduled for that unit based on:
    a. The maintenance occurring before the forecast failure date.
    b. The maintenance being applied to the most appropriate maintenance availability within the forecast time window.
    c. If no suitable maintenance period is available within the maintenance window then the subsystem is allowed to run to failure if the current operational period has less than required threshold in days to run.
14. Subsystems do not deteriorate during maintenance periods.
15. Subsystems do not fail during maintenance periods.
16. Subsystem Units are re-initialised at the end of the nominated refurbishment maintenance period or after a scheduled repair maintenance period.

These rules provide a basis for the logic governing the platforms and subsystem behaviour. The specifics of some of the rules attempt to simplify real life reactions. For example rule 10 defines the inclusion of a 14-day operational period reduction. This value can be used as sensitivity points to observe the effect of system efficiencies. It also represents the logistics delay time in getting the platform or spares to a repair venue of visa versa.

Model outputs

Model outputs, generated in Excel spreadsheets in table format, aid in model validation and present the modelling results. Validation data comprises an event log file showing model behaviour as data containing the modelling day, event and decisions flowing from that event. The logged information enables analysis of program flow and decision logic with consequences to be validated. A second set of data is used to measure the confidence interval of the generated data. Output results are used to communicate the model outcomes indicating quantitative consequences of selecting a particular maintenance policy. Earlier discussion of the maintenance system and its MOE’s identified that the number of consecutive operational days is important as well as the effect on maintenance time and the level of CBM applied.

Model Software Implementation

This model has been developed using Microsoft Excel® and Visual Basic® for Applications (VBA) in which agents are implemented as class Objects and the worksheets are used for input data, output data and control data.

Three main object classes are used. These are the Platform, Subsystem and Schedule. A maintenance class is considered for implementation at a later time to support maintenance venue queuing. In addition to classes the code is segmented into a main runtime loop and various modules supporting the report functions and decision analysis functions. Figure 4 shows the class hierarchy used.

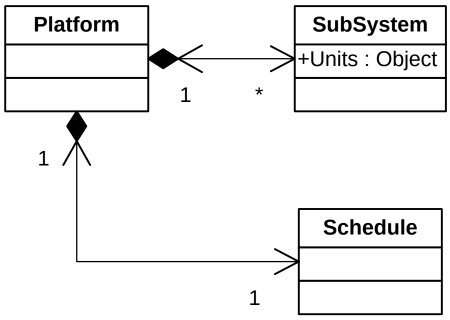

Figure 4 Class Structure

Model Verification & Validation

Verification has been undertaken as in iterative process through the definition and coding phases of this research. Because the process is largely a prototyping exercise, initial requirements have been reviewed and modified continuously. The output log allows subsystem events and decisions to be traced and reviewed.

The model inputs, specifically MTBF and usage factor, are mean values that are useful for providing a failure distribution for a meaningful population of like items over a reasonable sample. Therefore, the model will produce a distribution of outputs over many runs using the same input data. Paper (Nakayama 2008) provides methods for statistical analysis of Monte Carlo transient model output. This has been incorporated into the model to determine a representative confidence interval for each set of model runs. A series of experiments have determined that 50 runs per experiment provide a reasonable 95% confidence interval of around 20 days for 1 boat over 3650 days.

Maintenance Performance Modelling Results

The resulting model incorporates the decision rules discussed above. Outputs include platform availability within the operational periods and overall effective availability. A representative subset of 25 platform subsystems provides the test data for this exercise. Each of these subsystems has condition monitoring capability. The 25 subsystems are a representative subset of the total systems of the platform. Therefore, the analysis of data that we are interested in has to consider relative differences or changes between various scenarios rather than accept absolute values.

A series of 7 experiments were conducted. Each experiment comprises 50 runs of 3650 days model time. Experiment criterion is tabulated below.

Table 3 Experiments

#	Experiment Criteria	Platform Effectiveness (% of Sea Days)
1	1 platform with no condition monitoring.	48.7%
2	1 platform with condition based monitoring.	50.6%
3	6 platforms with no condition based monitoring.	50.65%
4	6 platforms with condition based monitoring @ 30%.	57.5%
5	6 platforms with Condition Based Monitoring @ 50%.	58.1%
6	6 platforms with Condition Based Monitoring @ 10%.	55.98%
7	6 platforms with Condition Based Monitoring @ 30% plus condition based preventive maintenance.	57.6%

Outcomes of the 1st and 2nd experiment show the available sea days achieved during each operational period out of a maximum mission days. The graphs show a improvement in sea days when maintenance decisions are based on data derived from condition monitoring.

Experiments 4,5 and 6 look undertake an analysis of the detection ability of the condition monitoring equipment. It confirms that as CBM sensitivity increases, sea days would increase because the prognosis and decision algorithms have greater opportunity to schedule maintenance before failure occurs. One would expect this to exhibit a positive effect on the total availability because maintenance can be undertaken at more opportune times. However, the same maintenance is undertaken and any additional maintenance detracts from sea days depending on when it is undertaken.

Analysis of total number of operational platforms available at any given time has been done in experiments 5 and 6. There is an small improvement when condition monitoring is added. However, the differences are not so great indicating that although maintenance can be better scheduled to retain continuous sea days, the maintenance still has to be completed at some stage and this will impact the number of available platforms.

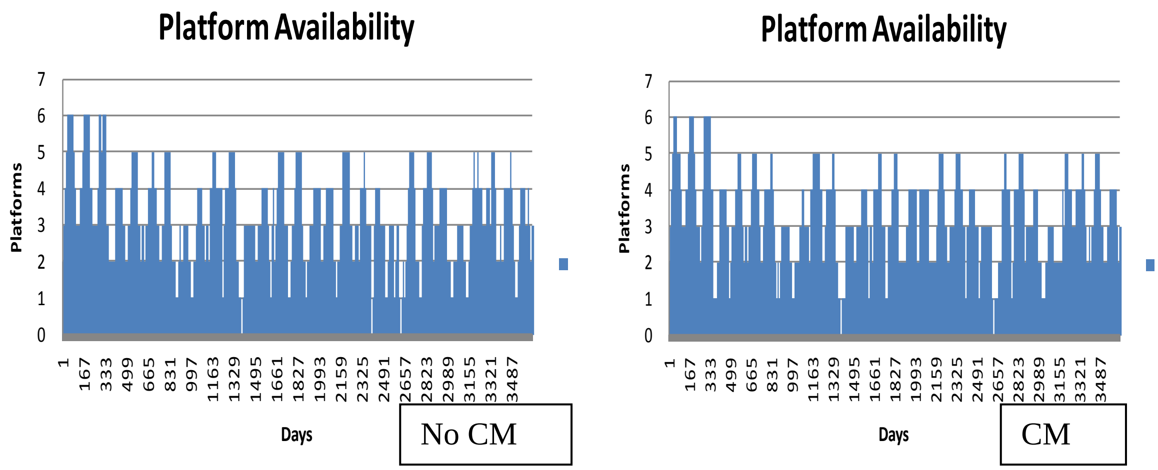

Figure 5. Platform Availability: without and with Condition Monitoring.

CBM Detection Sensitivity

CBM is effective because it provides advance warning of an impending failure through monitoring degradation of system components by monitoring certain characteristics. The standard model determines that detection of degradation is valid at 30% of the remaining life of a subsystem unit. This means that degradation is detected and reported in the last 30% of the life (MTBF) of the unit.

The earlier that the failure prognosis is made the greater the probability of correcting the problem within a suitable maintenance period. The sensitivity of the point of degradation detection is determined within all experiments. These experiments look at both single platform and 6-platform fleet scenarios measuring the effect on platform availability and average consecutive sea days. As the sensitivity of CBM increases, the average platform availability slightly decreases. This conflicts with average sea days values that increase as the sensitivity increases (see Figure 6). Availability values are reasonably steady.

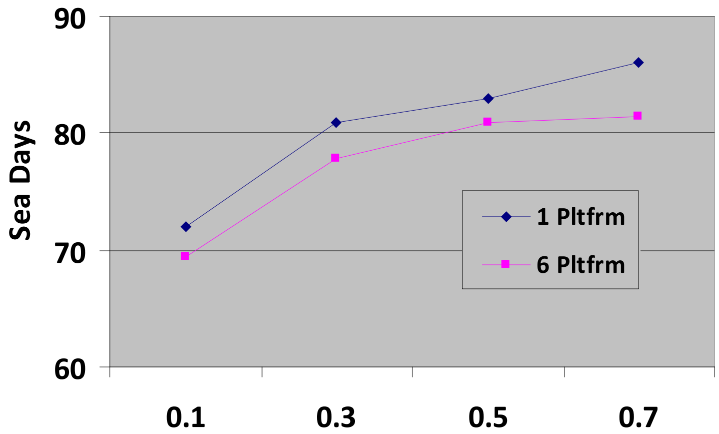

Figure 6 Condition Monitoring Sensitivity

Conclusion

Modelling the maintenance system of an in-service military platform does provide insight into how we can improve a maintenance process and how these improvements can be measured. Existence of the modelling software and ability to use it are the key preconditions for successful maintenance process change to achieve the desired benefits.

An issue that dominates maintenance improvement initiatives is the momentum required to change a maintenance policy for equipment or platform. Sign-off authorities require validation and preferably un-disputable fact that the change will result in an improvement and will be safe. In many instances sufficient historical data is not available to achieve this. By modelling the before and after scenario, some degree of assurance can be provided as to the outcomes to be expected based on the proposed changes made.

While this paper provides practical insight into the applications to which this model can be applied, there is much opportunity for further research to improve the model and to apply it to complete systems, subsystems, units and their many failure modes. We are still conducting modelling experiments and sensitivity analysis of the model behaviour using different assumptions. Those analyses give us greater insights to help formulate conclusions with more confidence.

Model limitations are being addressed with further consideration to implement an extended economic model by including costs estimation of maintenance services and use it a measure of maintenance performance.

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Biography

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