Predictive Life Cycle Forecasting: Innovative Decision-Making for Complex Asset Management in the Naval Environment

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Abstract Australia's warships and submarines are collectively the most complex, critical and expensive warfighting assets within Defence's inventory. Asset managers make decisions where beneficial short-term effects may cause unforeseen long-term repercussions leading to increased life cycle costs, decreased (or lost) capability and reduced operational availability that affect the operations and maintenance profile across each usage and upkeep cycle. Predictive life cycle forecasting provides an objective and empirical method to quantify budgetary requirements based on estimated future effects to operational readiness and seaworthiness. The life cycle forecast is a key component of each vessel's asset management plan and records the operations and maintenance profile across the asset's service life by establishing requirements for products and services needed to support the vessel within the prescribed asset management system. Predictive life cycle forecasting initially begins with establishing a baseline life cycle model that amalgamates contiguous operational running periods and scheduled maintenance activities across multiple usage and upkeep cycles to provide a time-phased representation that projects expected costs, operational availability and capability baselines from commissioning to disposal. Variable phases, states & modes provide the means to adjust model parameters to probabilistically characterise options available to asset managers when evaluating and assessing various scenario outcomes. An interactive model can provide asset managers with immediate feedback based on options explored within the model. Using each vessel's life cycle model, predictive life cycle forecasting can provide a consistent and logical method for systematically updating asset management plans. Robust and comprehensive predictive life cycle forecasting supports asset management decision-making to more accurately optimise warships' and submarines' availability, capability and affordability across the life cycle. As

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a fully scalable method, it can be applied to a single vessel, class of assets or to the collective fleet as a fundamental technique to support Fleet Life Cycle Management.

1 Introduction

Australia's national naval enterprise is a virtual organisation comprised of government personnel from the Royal Australian Navy (RAN) and Capability and Acquisition Sustainment Group (CASG) and commercial industry in the defence maritime sector. As a group, it designs, builds, sustains, operates and disposes of RAN vessels. Asset management has been identified as a core enterprise function. Department of Defence (Defence) sustainment policy mandates alignment to methods, practices and principles contained in ISO 55000, ISO 55001 and ISO 550002 (CASG 2017). The Fleet Life Cycle Management (FLCM) concept applies asset management to Australia's naval fleet through a framework that includes high-level Fleet Life Cycle Objectives (FLCOs) (Lemerande 2018). Enterprise decisions that affect individual RAN assets or the collective fleet should be made with the intention of meeting these high level strategic objectives, supported by lower-level asset management objectives, that reside at the forefront of any decision-making process. FLCM optimisation can be achieved through maximising the concurrent achievement of availability, capability and affordability across the life cycle of the collective naval fleet (Lemerande 2017). To optimise FLCM, the naval enterprise needs an objective and quantifiable method to improve decision-making capability uniformly throughout the enterprise. This paper describes how predictive life cycle forecasting (PLCF) can support enterprise stakeholders to make better asset management decisions during a vessel's service life to improve optimisation of availability, capability and affordability of the entire Australian fleet. Section 2 provides a brief overview of a ship's life cycle and highlights the symbiotic nature of operations and maintenance during its service life and discusses major considerations and key variables pertinent to PLCF. Section 3 discusses how modelling & simulation (M&S) techniques can be used to deliver PLCF to the naval enterprise. The conclusion summarises the benefits and opportunities PLCF can deliver.

2 Life Cycle of a Naval Vessel

Figure 1 graphically depicts the multiple phases of a ship's life cycle. During its service life, a naval vessel is either in a Maintenance Availability (MA) or an Operational Running Period (ORP) when assigned tasking and activities are conducted between consecutive MAs. A ship's service life schedule (SLS) is the time-phased plan of alternating ORPs and MAs between commissioning and decommissioning. MAs are conducted to ensure the ship can meet successive ORPs' availability and capability requirements. The SLS provides the time-phased constraints on which plans for predicting availability, capability and affordability can be based.

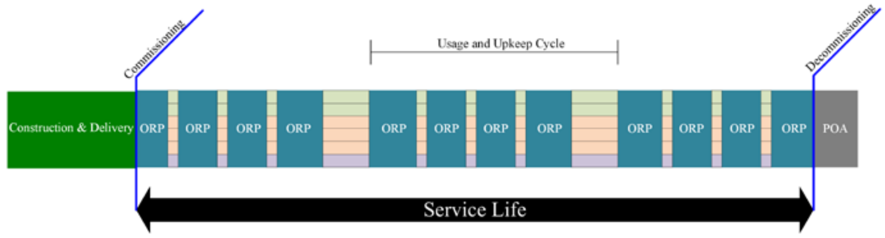

Figure 1 – Life Cycle for a Royal Australian Navy Ship

A Maintenance Availability Work Package (MAWP) contains all the work scheduled for accomplishment during a specific MA. There are six generic types of tasks contained in any MAWP, represented in Figure 2. A correctly scoped, planned and executed MAWP should deliver a vessel at the end of the MA that can meet its inherent reliability and performance characteristics as intended throughout the next ORP.

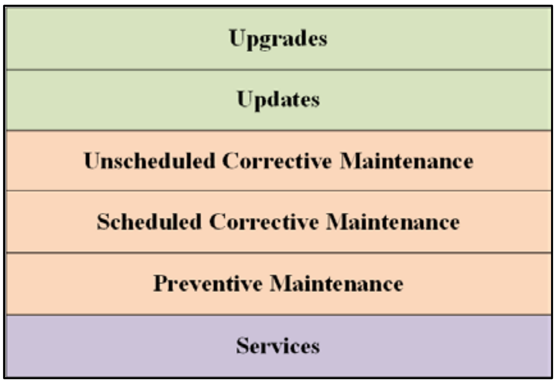

Figure 2 – Types of tasks within a Maintenance Availability Work Package

Upgrades and updates are two types of modernisation activities. Updates replace older equipment or parts with newer versions or components to improve reliability or prevent future logistical problems due to obsolescence or parts unavailability. Upgrades are modifications to ships or ship systems that will increase or improve military capability or functionality. Maintenance, or upkeep, can be either preventive or corrective and seeks to restore equipment to its intended operating condition. Preventive maintenance is predetermined work that is either time-based or respondent to conditional factors and aims to keep equipment and systems operating at or above designed performance levels. Corrective maintenance, which can be categorised as either scheduled or unscheduled, seeks to rectify deficiencies and restore equipment, components and systems back to minimum acceptable levels of performance in accordance with technical specifications. Scheduled corrective maintenance are known deficiencies that can be properly scoped and planned prior to the MA; unscheduled items are new deficiencies that were previously unknown or identified as growth from poorly scoped known deficiencies. Service tasks consist of support provided to the ship's crew and maintenance service providers that are necessary to accomplish work during a MA. Some common examples of services provided during a MA include: temporary electrical power; ventilation; compressed air; air conditioning; potable water; sewage and waste removal; rigging and lifting & handling; scaffolding; and activities required for dry docking

During an ORP, a ship should be able to conduct one of four different types of activities: trials & material certification; military exercises; unit specific training or training within a larger task group or force; and missions to achieve operational objectives. A commissioned ship exists in one of several different states of material readiness. Figure 3 identifies generic states & modes a vessel will occupy across its service life.

States
I - Available, Capable, Deployable
II - Available, Capable, Not Deployable
III - Available, Not Capable, Not Deployable
IV - Not Available, Not Capable, Not Deployable

		At Sea		Alongside			Dry Dock	
		Op Area	In Transit	Home Port	Australian Port	Foreign Port	Home Port	Other
Operations	Mission	I	I	I	I	I		
	Exercise	II	II	II	II	II		
	Training	II	II	II	II			
	Trials/Certification	III	III	III	III			
Maint	Operational Maintenance Period			III	III	II		
	Scheduled Maintenance Availability			IV	IV		IV	IV
	Emergent Maintenance Period			IV	IV	IV	IV	IV

Figure 3 – States & Modes of an In-Service Naval Vessel

States I through IV have been identified through various combinations of a vessel being available, capable or deployable and paired with the appropriate geographic location and activity a ship must undertake. "Available" means a ship has the ability to safely put to sea and get underway under its own power. Not available means a ship is unsafe to go to sea or requires assistance to get underway and transit to another location. "Capable" means the ship's material condition enables it to safely conduct its assigned mission(s) or tasking. Not capable means the ship cannot fulfil these functions. "Deployable" means the operational commander has designated the ship for deployment and the vessel can execute the assigned mission. Thus, a naturally escalating hierarchy exists that must be preserved: a capable ship must be available; a deployable ship must be capable and thus is also deemed available. (A ship that is capable but not designated for deployment will not be deployable even though the material condition may support being in the deployable state.)

Modes are best characterised by the ship's generic location, employment and activity. Geography is the identified type of physical location; a ship is either at sea, moored alongside a pier, or docked ashore. A ship at sea is either in the designated operational area or transiting to or from it. A moored ship is berthed either overseas or in Australia where it can be in its home port or some other Australian port. The same applies to dry dock periods, depending on the location of the maintenance service provider. In each of these modes, a ship will exist in a single state at any given time. However a ship can be in more than one state for certain modes but can never be in two states simultaneously, just as it cannot be in two modes simultaneously.

Each combination of states & modes represents a unique condition for the given ship. States & modes are critical to PLCF because they correlate directly to "state changes" inside the model discussed in the next section. These unique combinations make up discrete conditions. Moving from one condition to another is signified by a change of states or "state change" that will be used in M&S software for PLCF.

3 Predictive Life Cycle Forecasting

Planning for an economically managed fleet includes forecasting costs associated with operating, maintaining and modernising shipboard equipment across the life cycle. Forecasts must be time-phased and specifically identify discrete activities within each ORP and MA. These activities are dynamic and, thus, are variables that when adjusted, will alter any future predictive plans. Forecasting should be based on the time-phased activities expected to occur in alternating ORPs and MAs. When considering optimisation of FLCM, these forecasts must evaluate the effects on availability, capability and affordability.

Forecasting techniques are classified as two general types: qualitative and quantitative. Quantitative forecasting techniques are objective and based on mathematical and statistical methods that relies on data (Al-Fares and Duffuaa 2009) and analytics. Qualitative forecasting methods rely on experts to apply expertise to make judgments based on intuition and expertise to produce informed estimates about the future (Goetschalckx 2011). The FLCM concept requires an approach to utilising quantitative forecasting as much as possible to remove the subjectivity from the approach to life cycle management. Forecasting should cover the fleet's perpetual life cycle and be predictive in nature. Life cycle activities can be evaluated in three distinct categories – capability, availability, affordability – by amalgamating individual ship's data into a larger repository that assesses the entire fleet. This information can be represented in separate forecasted plans to which actual performance can be compared. The SLS establishes the time-phased plan for ORPs and MAs and tags specific states & modes to discrete periods within those activities. It provides the baseline upon which service life plans can be made.

3.1 Service Life Model

FLCM requires an enterprise architecture that accounts for every ship in the fleet and other support systems to provide a holistic and inclusive management environment (Lemerande 2018c). Within this architecture, each ship's service life model (SLM) would contain all pertinent information for ORPs and MAs and should be built using Systems Modeling Language (SysML) because the model can be partitioned into four distinct categories: structure, behaviour, requirements and parametric relationships (Grobhstein, Perelman, Safra and Dori 2007). SysML will enable a tailored method for focussing limited time, effort, money and human resources (Lane and Bohn 2012) on the most important and applicable aspects the SLM. SysML's functionality supports a hierarchical structure and facilitates the scalability and commonality needed to consolidate multiple SLMs into the fleet-wide model.

The model structure can establish a common ontology and define the basic structure and process architecture as it specifically applies to PLCF. Key parameters within the model that can be varied should include: dates and durations of each MA; the allocation of states & modes within each ORP; and the contents of each MAWP across the service life. These parameters within the SLM's structure will produce three separate plans that forecast availability, capability and affordability across the service life. All SLMs should contain the same basic structure as a way to facilitate scalability and easy amalgamation of all SLMs into the complete FLCM portfolio. This will enable forecasted plans to be combined into a composite representation of the entire fleet.

3.2 Forecasted Plans

RAN ships must be routinely modernised by installation of updates and upgrades throughout its service life. These updates and upgrades should be allocated to scheduled MAs and included in MAWPs. Figure 4 shows incremental capability increases resulting from updates and upgrades being installed during scheduled MAs. Capability increases can be quantified through linkages to a Functional Performance Specification (FPS) or other capability measurement function within the FLCM architecture. Just as updates and upgrades are assigned to MAWPs, all types of maintenance in MAWPs must be allocated to specific MAs to support availability predictions and forecasts. Cumulative availability increases during ORPs but flatlines during MAs, shown in Figure 5, or whenever the required material readiness state cannot be met. Future availability is heavily dependent on the makeup and composition of each MAWP because it is highly reliant on the appropriate maintenance being conducted within each MA. Availability forecasts, collated from individual ship models, provide the data for incorporation into the consolidated fleet-wide model. Cost estimates for discrete ORP and scheduled MAs can be quantified based on the expected tasking and length of scheduled sustainment periods. Maintenance, modernisation (i.e. updates and upgrades) and MA services are crucial elements within life cycle planning; they undoubtedly affect financial programming and budgeting efforts regardless of the expected service life. ORPs are often prorated to account for fuel, ammunition, victuals and other recurring actions required to support maritime operations. For MAs, each MAWP can be estimated based on the known services, expected maintenance and planned updates and upgrades. Estimates will yield overall summations that are based on labour and materiel. Total material costs and labour rates applied to expected (or allocated) efforts will produce a cost profile across a ship's service life similar to that depicted in Figure 6. Service life plans' data will provide useful, pertinent and necessary information for the PLCF concept.

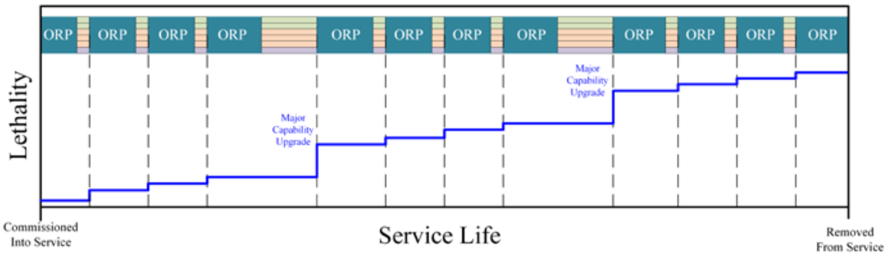

Figure 4 – Forecasted Service Life Capability Plan

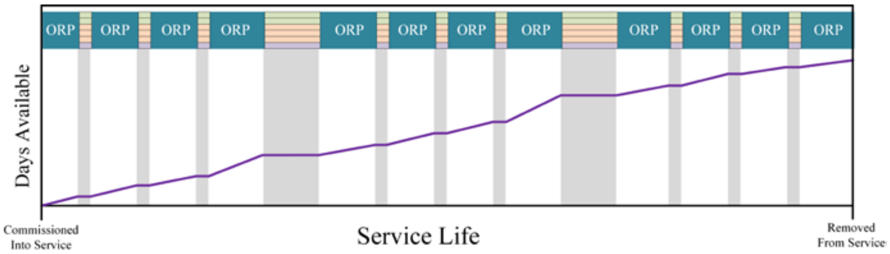

Figure 5 – Forecasted Service Life Availability Plan

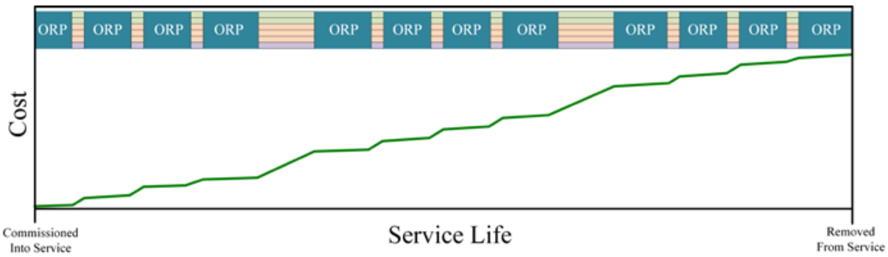

Figure 6 – Forecasted Service Life Affordability Plan

3.3 Decision Support from Discrete Event Simulation

Decision support through algorithms or software tools help stakeholders and decision makers consider implications and consequences of options and courses of action. Simulation is an effective technical means for system(s) optimisation. Decision support tools are designed to improve decision-making processes for complex systems and are widely used to assist decision-makers who must consider wide ranging areas. Discrete Event Simulation (DES) simulates operations by stepping through time and skipping periods where no changes occur. This method is desirable in that implementation is easy, execution time is relatively short and the environment is flexible (Griendling and Mavris 2011). DES works well when states & modes are clearly defined because these become "state changes" and can easily be modelled. For a dynamic system characterised by complexity and uncertainty, as would be encountered by dozens of naval ships across 30 or more years, DES offers a powerful way to gain insight and knowledge about the system. In DES, abstract system models use a continuous but bounded time base where only a finite number of relevant events occur. These events cause state changes within the system which are then evaluated within the model to determine the effects on the overall system. DES is the method by which stakeholders and modellers can collaborate to explore different courses of action through "optioneering" by changing key variables within SLM(s) and executing simulation on the consolidated fleet model and observing the results for each forecasted plan.

3.4 Optimisation Through Optioneering

MAs are key drivers for parts, material and services which account for a significant portion of the Life Cycle Cost (LCC) attributed to a ship's the service life. Accurately forecasting MAs and all the elements that contribute to effective maintenance periods are critical to FLCM. MAWPs are susceptible to significant change and can be the source of significant disruption to a forecasted plan. ORPs can also be extremely dynamic. This aspect of the SLM has many states & modes that can be varied within simulations. Moreover, unexpected state changes due to emergent operational requirements or unplanned repairs can wreak havoc on a forecasted plan. Costs predicted for each MA and ORP, when tallied across a ship's service life, can produce a cumulative summary. However, when contents of MAWPs change or operational schedules change, the associated costs will also be affected. The dynamic nature of both ORPs and MAs necessitates the SLM be flexible, simple in its design and robust to handle significant changes within the consolidated fleet model. It must also give modellers the ability to change the environment to allow exploratory simulation that produces objective and quantitative results that can be easily compared.

In PLCF, optioneering is the method by which this dynamic nature can be managed. Optioneering allows stakeholders and decision-makers to stimulate imagination, visualise possibilities and quantify the magnitude of change while revealing alternatives and trade-offs associated with different options. It seeks to use high-end computing capability to reduce latency, increase integration amongst contributing factors and deliver quantifiable evaluation of various alternatives (Gerber and Flager 2011). Furthermore, it also allows stakeholders to explore various and more complex solution possibilities through simulations and optimisation methods like DES without relegating this work solely to engineers or designers (Gerber, Lin, Pan and Solmaz 2012). Using the tools and models available in the PLCF concept, optioneering allows stakeholders and decision-makers to use M&S to explore multiple scenarios and observe how the results affect the fleet's overall availability, capability and affordability in the short-, medium- and long-terms.

4 Conclusion

PLCF, as described in this paper, can provide a scalable decision support mechanism that gives naval enterprise stakeholders an ability to explore numerous scenarios through dynamic M&S techniques in order to validate or refute different potential options for a single ship and observe the effect at the consolidated fleet level. PLCF, if developed and implemented using appropriate M&S, will provide naval enterprise stakeholders with improved decision-making capabilities that can better support optimisation of availability, capability and affordability throughout the naval fleet in the coming decades.

References

Al-Fares, H.K. and Duffuaa, S.O., 2009. Maintenance Forecasting and Capacity Planning. In Handbook of Maintenance Management and Engineering (pp. 157-190). Springer, London.

Buede, D.M. and Miller, W.D., 2016. The engineering design of systems: models and methods. John Wiley & Sons.

Capability and Acquisition Sustainment Group, 2017. Functional Policy (PM) 001: Sustainment Management in Capability and Acquisition Sustainment Group Vers 2.0. Canberra: Commonwealth of Australia, 11 August 2017.

Gerber, D.J. and Flager, F., 2011. Teaching design optioneering: a method for multidisciplinary design optimization. In Computing in Civil Engineering (2011) (pp. 883-890).

Gerber, D.J., Lin, S.H.E., Pan, B.P. and Solmaz, A.S., 2012, March. Design optioneering: multi-disciplinary design optimization through parameterization, domain integration and automation of a genetic algorithm. In Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design (p. 11). Society for Computer Simulation International.

Goetschalckx, M., 2011. Supply chain engineering (Vol. 161). Springer Science & Business Media.

Griendling, K. and Mavris, D.N., 2011, March. Development of a dodaf-based executable architecting approach to analyze system-of-systems alternatives. In Aerospace Conference, 2011 IEEE (pp. 1-15). IEEE.

Grobshtein, Y., Perelman, V., Safra, E. and Dori, D., 2007, March. Systems modeling languages: OPM versus SysML. In Systems Engineering and Modeling, 2007. ICSEM'07. International Conference on (pp. 102-109). IEEE.

Lane, J.A. and Bohn, T., 2012. Using SysML modeling to understand and evolve systems of systems. Systems Engineering, 16(1), pp.87-98.

Lemerande, T. J, 2017. Optimising Availability, Capability and Affordability Across the Fleet: A Total Life Cycle Management Approach to Improving Seaworthiness. In e-Proceedings of 12th Annual World Congress on Engineering Asset Management. Brisbane, 2-4 August 2017.

Lemerande, T. J., 2018. Leading the Naval Asset Management Effort with a Framework for Fleet Life Cycle Management. E-proceedings of AMPEAK 2018: Hobart, Tasmania 16-18 April 2018.

Lemerande, T. J., 2018. A System of Systems Approach to Developing a Digital Asset Management Environment for the Naval Enterprise. Systems Engineering Test and Evaluation Conference 2018, International Council on Systems Engineering (INCOSE): Sydney 30 April - 2 May 2018.