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MB-PLE to Plan and Track Submarine Configurations

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Abstract. The life of a class of submarines can be measured in decades. As such the operational demands and expectations change both strategically and tactically over its lifetime. Coupling this adaptability with the length of time submarines take to design, build, and maintain, no two "as built" submarines in a class will ever be the same even when constructed/maintained to the same "build to" design. Traditionally this has been accepted as the case and in most cases the full information set has been managed via the configuration management team at a class or batch level but not at an individual submarine level. The configuration of an individual submarine has been managed in terms of agreed changes against the class or batch baseline. Advances in technology (hardware performance, software tools and standards) now give us the opportunity to not only manage the full information set related to individual submarine system configuration baselines as they change over time but also undertake rigorous model based trade-off studies to plan the manner in which a class, a batch, an individual submarine (variant), or any combination thereof can be modified over time. This paper will explore the use of Model-Based Systems Engineering (MBSE) coupled with recent developments of Product Line Engineering (PLE) / Orthogonal Variability Modelling (OVM) to provide a means to plan, track, manage and evaluate an individual submarine's configuration over time in the context of the class, whilst simultaneously highlighting the wider application in the submarine enterprise and beyond.

INTRODUCTION

The life of a class of submarines can be measured in decades. As such the operational demands and expectations change both strategically and tactically over its lifetime. As a major military asset the submarine, and the enterprise operating and supporting it, needs to adapt both in the long term, to deal with strategic changes (change of operating conditions, Government policy changes, new threats, etc.) as well as routine obsolescence issues and emerging technology opportunities. In the short term, it must deal with tactical changes (different weapon outload mixes, sensors or countermeasures) as well as equipment defects and failures. Coupling this adaptability with the length of time submarines take to design, build, and maintain, no two "as built" submarines in a class will ever be the same even when constructed / maintained to the same "build to" design. Traditionally this has been accepted as the case and in most cases the full information set (requirements, designs, analysis results, procurement specifications, software documents, handbooks, etc.) has been managed via the configuration management team at a class or batch level but not at an individual submarine level. The configuration of an individual submarine has been managed in terms of agreed changes against the class or batch baseline. This has resulted in much of the knowledge being retained in senior staff or only obtainable by visiting the specific submarine to determine its actual layout and configuration. The announcement of a rolling acquisition strategy for Australia's future submarine fleet in the 2016 White Paper (Australian Government Department of Defence, 2016) adds further to the need for better methods of managing submarine variations over time.

Advances in technology (hardware performance, software tools and standards) now give us the opportunity to not only manage individual submarine configurations as they change over time (traditional configuration management) but also undertake rigorous model based trade-off studies to plan the manner in which a class, a batch, an individual submarine (variant), or any combination thereof can be modified over time (proactive management through analysis and planning). Due to the complexity of a submarine and its operating environment; evaluating the competing configurations at the equipment or component level has historically resulted in a detailed, time consuming set of studies which have proven extremely difficult to aggregate and assimilate. Evaluating configurations at the abstract systems engineering level with the advance in computing power and available Systems Engineering methods (Product Line Engineering – PLE) can provide an agile means of evaluating alternative configurations to any level of abstraction or level of detail in measures of time by defining the different configurations for both time scales and mission purpose. This paper explores the potential of using Model-Based Systems Engineering (MBSE) coupled with recent developments of Product Line Engineering (PLE) / Orthogonal Variability Modelling (OVM) to provide a means to plan, track, manage and evaluate an individual submarine's configuration over time in the context of the class, whilst simultaneously highlighting the wider application in the submarine enterprise and beyond. (Stricker, 2012)

MODEL-BASED SYSTEMS ENGINEERING

MBSE techniques are widely recognized as industry best practices to model and define the system, maintain the model through time and provide the framework for subsequent systems engineering and analysis. MBSE methods are underpinned by a language known as the Systems Modelling Language (SysML). For large scale, complex Systems of Systems (SoS) the Unified Profile for DoDAF and MODAF (UPDM) exist to relate Systems to one another and the detailed constituent breakdown of individual systems. UPDM implements the Department of Defense Architecture Framework (DoDAF), the Ministry of Defence Architecture Framework (MODAF) and the NATO Architecture Framework (NAF) using SysML. (DoDAF 2014) (OMG, 2012) This provides a means of performing systems engineering on the entire SoS rather than simply capturing the architecture as a collection of models using a common set of methods. Recent versions of UPDM architectures can now take the fourth dimension (time) into account. (UPDM, 2012) The paper "Architecting in the Fourth Dimension - Temporal Aspects of DoDAF" (Hause, Kihlstrom 2013) captures many of these aspects. However, the management of the configurations, assembly of them, analysis, engineering and generation of variations of the configurations requires an additional technique. This is provided by a method known as Model-Based Product Line Engineering (MB-PLE).

Elements of SYSML

SysML defines the properties of each system element and the relationships between system elements as well as providing visual representation through a series of diagrams. The SysML diagrams can be used to specify system requirements, behavior, structure and parametric relationships. These are known as the four pillars of SysML. The system structure is represented by Block Definition Diagrams and Internal Block Diagrams. A Block Definition Diagram describes the system hierarchy and system/component classifications. The Internal Block Diagram describes the internal structure of a system in terms of its Parts, Ports, Interfaces and Connectors. Parts are the constituent components or "Parts" that make up the system defined by the Block. Interfaces define the access points by which Parts and external systems access the Block. Connectors are the links or associations between the Parts of the Block. Often these are connected via the Ports. The parametric diagram represents constraints on system parameter values such as performance, reliability and mass properties to support engineering analysis. Taken together, these constructs are used to represent complex systems. (OMG, 2012), (Friedenthal, 2011)

EXAMPLE SUBMARINE DESCRIPTION

For the purposes of this paper a simplified class of generic Diesel/Electric submarine will be used to examine the applicability of Product Line Engineering/Orthogonal Variant Modelling techniques across the lifecycle of the class. In the example, the class will follow a traditional design, build, maintain paradigm and consist of three batches of three submarines. The simplified generic submarine will consist of the following major systems, as shown in Figure 1:

- Pressure Hull, Casing and Fin;
- Propulsion and Maneuvering;
- Power Generation and Distribution;
- Platform Management and Control;
- Combat Management;
- Communications;
- Platform Services;
- Accommodation;
- Intelligence, Surveillance and Reconnaissance (ISR) Sensors;
- Weapon management and stowage.

Each batch of submarines will have different capability requirements and detailed design. Each submarine within a batch will have the same “build to” design but will incorporate lessons learnt during the construction and integration of earlier submarines and the available updated hardware and software components to the extent that the “as built” of each submarine, even within a batch, will not be identical. This means that each submarine is a unique variant of the design baseline, has its own information set and needs to be configuration managed as a unique item throughout the course of its entire lifecycle. It also means that it is simultaneously linked to and derived from the batch and class designs.

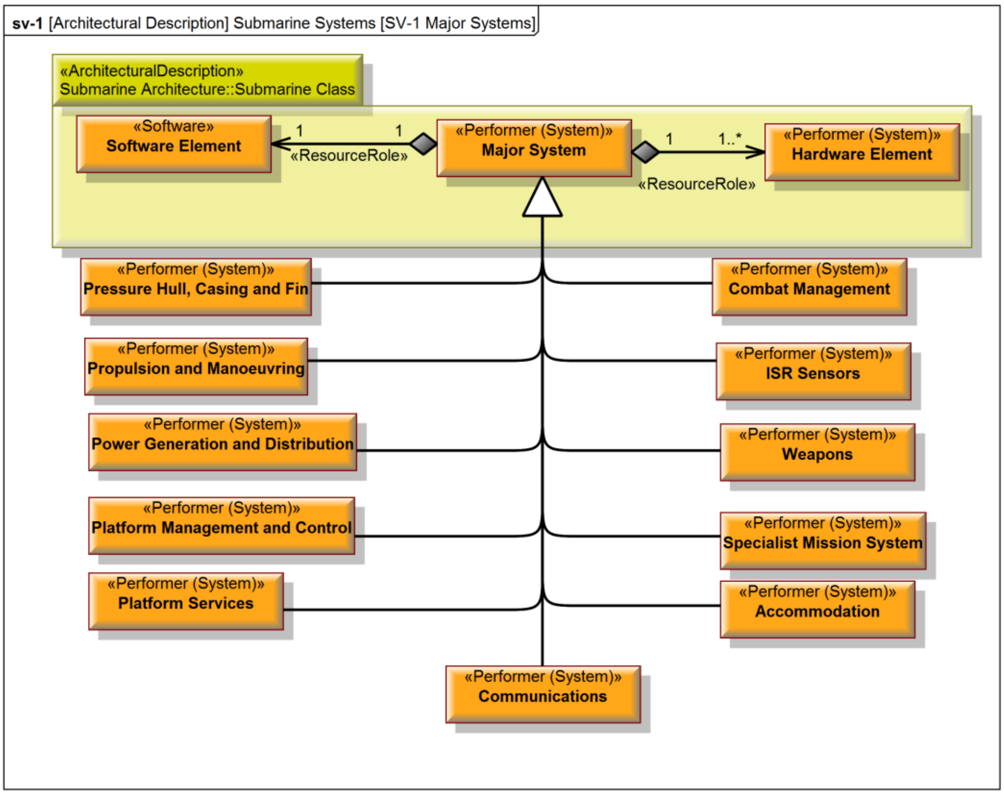

Figure 1. Major Submarine Systems

Example Submarine Timescales

The timeframes depicted in this example are for the purpose of this paper and do not reflect those of any existing or proposed class of submarine. Each batch will have a different initial capability and technology baseline. Within each batch each submarine will have the same basic capability and "build to" design; individual submarines will be delivered (built) at 2 year intervals. In parallel to the submarine design, construction and maintenance efforts the following major systems will be undergoing significant development and enhancement throughout the submarine lifecycle:

- Combat Management System:
  - Continuously enhanced through development of new software major baselines (2 year cycle) and hardware technology refreshes (5 year cycle).
- Platform Management System:
  - Software is updated for each submarine built and then at 5 year intervals throughout the submarine's life; and
  - Hardware is refreshed as each batch is built and at 10 year cycles thereafter.
- New communications inboard hardware updated after 15 years.
- ISR Sensors:
  - Mast mounted sensors:
    - Refreshed every 10 years; and
    - Fitted as needs dictate (i.e. mission needs).
  - Sonar:
    - Inboard hardware refreshed every 10 years;
    - External hardware updated after 20 years; and
    - New Software major baseline every 3 years.
  - Weapons:
    - Weapon outload will be mission specific and therefore different each time the submarine sails.
    - Weapon management software and stowage arrangements may vary depending on the weapons embarked.

Note: Weapons themselves have not traditionally been considered part of the submarine from a configuration management point of view but with the use of the modelling techniques described in this paper it is now possible to manage the submarine configuration on a mission by mission basis. This could be the same capability implemented to different levels or additional capabilities.

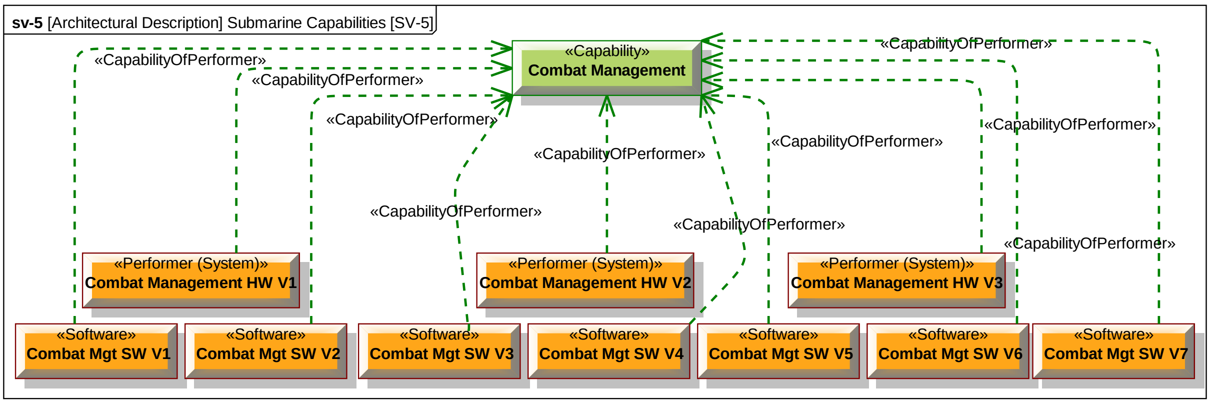

Figure 2. Combat Management HW and SW

Figure 2 shows the Combat Management Hardware and Software systems and their supporting relationships to the Combat Management capability. The Capability of Performer relationships indicate that these systems and software support or implement the Combat Management capability. Having defined the different systems that support the capability, it is necessary to show when these systems and software will be available. This is done using the UPDM project views. In this view, different projects are created for the development, creation, deployment and retirement of these systems. Figure 3 shows a simplified version of the changes of Combat Management system and software throughout the life of the submarine class.

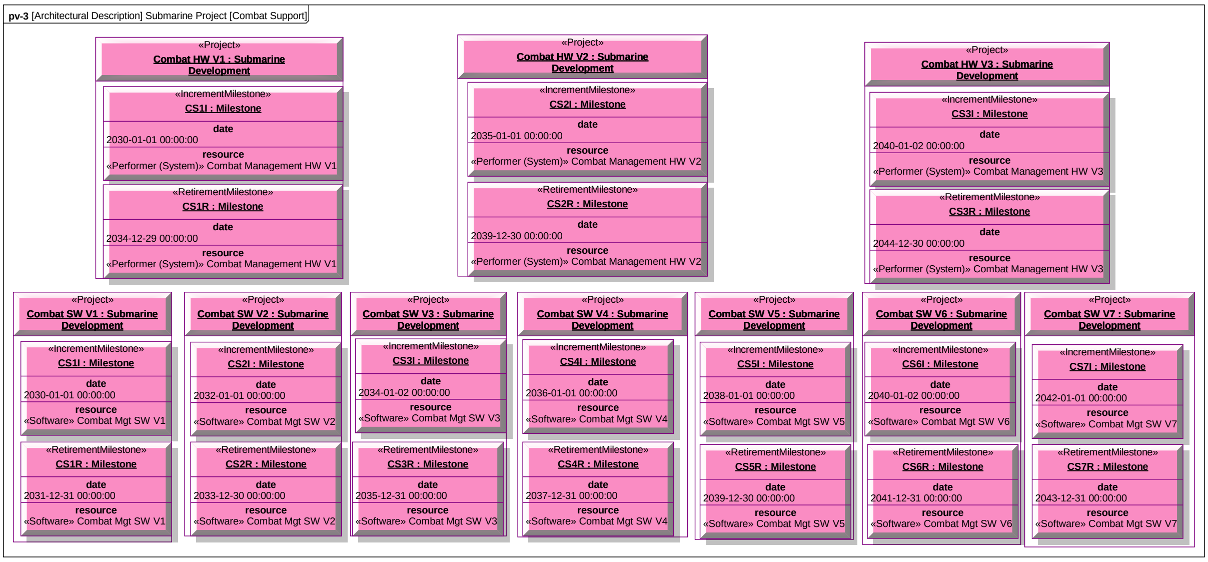

Figure 3. Combat Management HW and SW Projects and Milestones

Each project contains the increment milestone where the system becomes available and the retirement milestone, when the system is retired or no longer available. Figure 4 shows a timeline generated from the model data shown in Figure 3 that provides the project team with a simple understanding of the hardware and software deployment program supporting continuous improvement of the Combat Management System. It is important to point out these diagrams are automatically generated based on the data and relationships authored in the model.

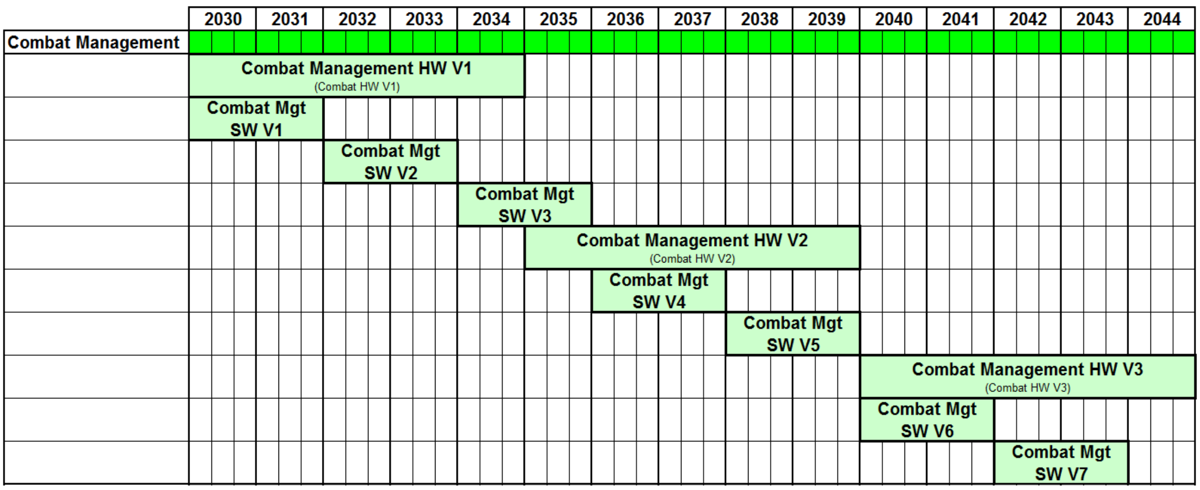

Figure 4. Combat Management HW and SW

PRODUCT LINES

A Product Line is a group of related products manufactured or produced within or between collaborating organizations. To effectively manage a product line, engineers need to understand both the similarities and differences between the different products and optimize the development lifecycle to leverage the similarities, and concentrate development on the differences. OVM provides the ability to model systems and software product lines, their variation points, the resultant variants and their variability relationships such as mutual exclusions and product dependencies. OVM was developed by the University Duisburg-Essen, PALUNO Institute (K. Pohl et al, 2005) and is now an ISO standard (ISO 26550: 2013, Reference Model for System and Software Product Line Engineering and Management). Through this modelling technique, engineers have the ability to design variability options, constraints and conflicts, (if any exist) and to pick their desired end product(s) by deciding on the variability options. (Heuer, 2010) In the case of a submarine, an example of a simple variation point might be electrical energy storage technology and the variants could be fuel cell, lithium ion battery and lead acid battery. A more complex example of a variation point might be a combination of electrical energy storage technology, electrical power distribution architecture, electrical generation method and the definition of compatible configurations. At the underwater warfare capability level, a variant point might relate to the best mix of airborne, ship based, submarine based, unmanned vehicle based and static sensor systems to prevent adversarial underwater assets from undertaking intelligence gathering activities in a nation's territorial waters. After modelling the variability in the product line model, the engineer can create decision sets and then choose to include or exclude variants for those decisions sets. Combining these with an execution engine means that product models can be created for specific products, whilst maintaining the original product line model. For system models, these aggregations of architectures are all captured in a single product line model and the configurations specified using OVM – from the architecture level right down to the component level. These models are multi-dimensional as well and not only capable of representing the physical configurations, but can also capture performance metrics, requirements, capabilities, functional specifications, scenarios, etc. Individual configurations can then be generated. Typical system engineering activities such as trade-off studies can be performed on these models as whole or even subsets of the model to ensure the overall system is fit for purpose. When problems with components are found, whether in related system design stages or deployed on a mission, the impacts of proposed configuration changes can be readily assessed at the submarine, batch, and class levels. This provides significant benefits for engineers trying to capture and demonstrate the different configurations of the system and allow cost effective, lower risk options for the submarine project as a whole to be identified. After modelling the variability in the product line model, the engineer can even create decision sets and then choose to include or exclude variants for those decisions sets. These can either be implemented or retained in the baseline for future consideration.

VARIANT MODELLING

As stated in the previous example, there is an accompanying language set that defines Variability Modelling. The following variability elements comprise the variability model:

- Variant: an option that can be chosen for a Variation Point.
- Variation Point: a variable product line feature whose options are defined through Variants
- Dependency
    - Variability Dependency: specifies that a Variant is an option for a Variability Point.
    - Excludes Dependency: specifies that the inclusion of a Variant or Variation Point requires the exclusion of another Variant or Variation Point.
    - Requires Dependency: specifies that the inclusion of a Variant or Variation Point requires the inclusion of another Variant or Variation Point.
- Alternative Choice: groups a set of Variability Dependencies and specifies the number of Variants that need to be included.
- Artefact Dependency: a special Dependency which specifies that an artefact (any base model

item) is associated with a Variation Point or Variant. It is the link between the Variant Model and the System or Software Model.

Use in Submarine Design.

For submarines, the different configurations would be specified via Variation Points and variants. To capture system configurations over time, the Variation Point becomes the time period, and the Variation Points are the time periods or epochs for those configurations. A combined product model would show several batches of submarines, individual boats within the batch, and the evolution of each submarine over time. Variation Points would be added for each batch as well as each boat in addition to time.

Figure 5 shows an example of the notation making use of several of the features of the Combat System of the submarine. The diagram shows the Combat System Variant Point related to Combat Management Hardware versions 1 and 2. Note it shows that Combat Management Software v3 requires Combat Management Hardware v2 and that Special Fit Sensor 1 and Special Fit Sensor 2 both require Combat Management Software v3 but cannot be utilized within the same submarine configuration, shown via the "excludes" relationship. Dependencies can also be constrained by a minimum and maximum number of possible choices. The syntax is <min>..<max> next to an arc connecting the Variability Dependencies.

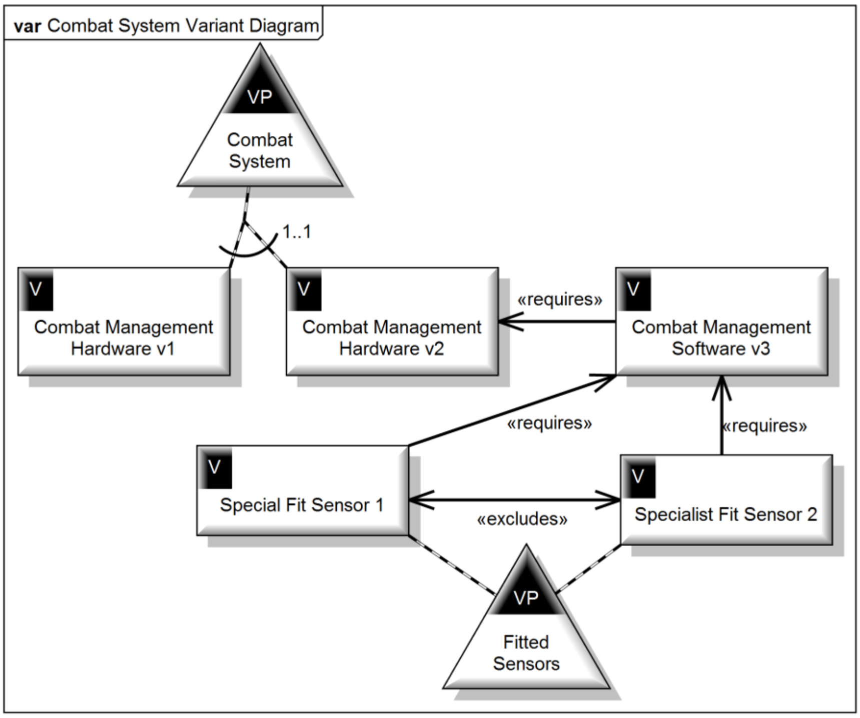

Figure 5. Combat Systems Variants

Integrating OVM and MBSE

The Variant Model represents the Product Line Model, frequently referred to as the 150% Model or the Overloaded System Model. This is a full representation of the Product Line, with all of its commonality and variation. To enable this, OVM elements can be integrated into the SysML Model and linked with any relevant model elements. Connections between Variable elements and the model elements allow engineers to model which system elements are in the product family model due to a specific variant or variation point. Artefact Dependencies can be created to all types of base model elements including Structural Dependencies such as Blocks or Parts and Behavioral Constraints such as Use Cases, Transitions or States. In order to express these dependencies, base model elements can be shown on Variability Diagrams and Variable Elements can be shown on other Diagrams as shown in Figure 6.

This variation differs from the SysML inheritance relationship in that it not only indicates the choices which can be made but it also allows engineers to use a separate (or orthogonal) nomenclature for the variations, choices and constraints that are available in the more technical Base Model. This is particularly useful when cross functional team members need to make product decisions, based on the rules documented by the product line engineer within the model. In today's world, understanding these choices and constraints is extremely difficult even on decisions of a contemporaneous nature when in reality these decisions are only re-examined years into the future. Additionally, complex multi-level decision sets are impossible to model in the base modelling languages, such as SysML. In order to properly express the model variability and not simply the model structure, an orthogonal modelling construct is required.

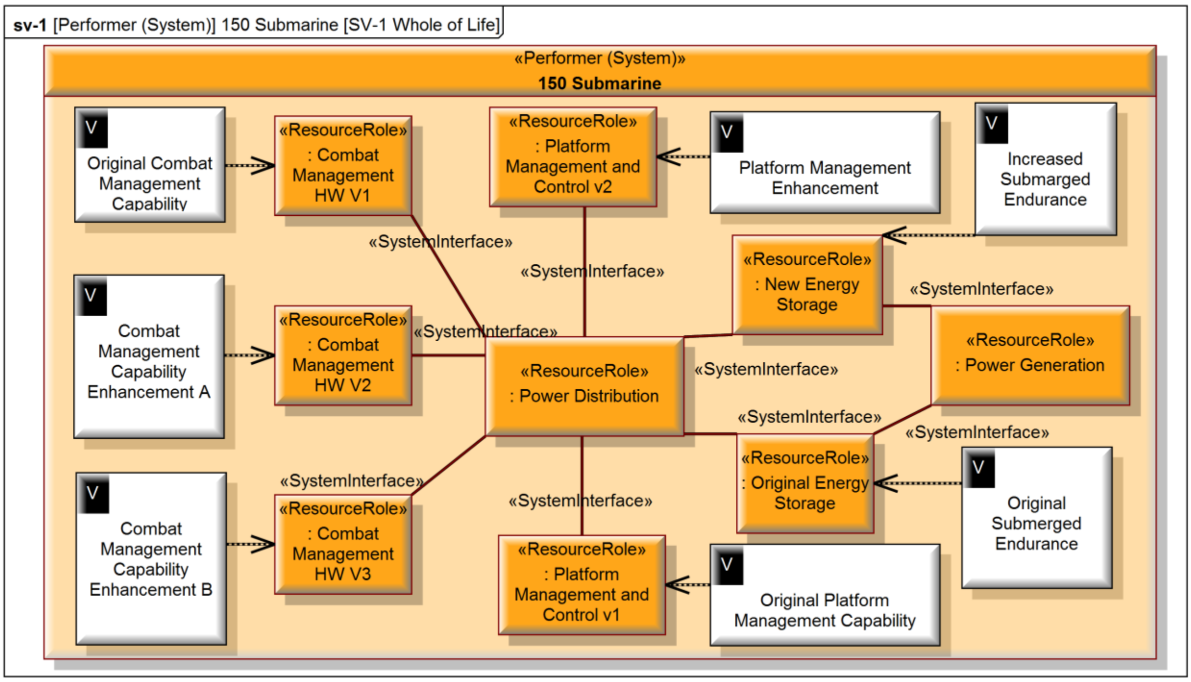

Figure 6. Submarine 150% Model

Variation and Dependency Modelling are key concepts frequently encountered in submarine design. Today, these factors are manually managed. Figure 6 shows an example of 150% Model of a submarine. In this example there are two different Combat Systems and two different Energy Storage solutions. These are connected to the Power Distribution and Power Generation systems. They are also linked to the variants corresponding to the system choices. In Figure 7, these systems are also linked to the timeframes of equipment availability. This provides a means of making configuration decisions based on desired capability as well as timeframe. These decisions points can be useful for identifying conflicts in configuration choices. For example, equipment may not be available during a specified timeframe, or combinations of equipment may be incompatible.

Variability modelling during design

During the design of a submarine there are many points where options are studied and decisions made about the design. Naval Architects traditionally record whole boat decision points and design versions using pen and paper or in their digital equivalents: Microsoft Excel™ and Microsoft Word™. Engineers designing major systems within the submarine also record their trade studies in Microsoft Excel™ and Microsoft Word™. Although this approach has worked in the past, the geographically dispersed nature of the design team on modern military platforms, such as a submarine, means that it is possible for important information generated during design, such as trade study options and dependencies, to become detached from the system during subsequent phases of the submarine's lifecycle. This makes the future design, maintenance and upgrade of the submarine more difficult, less efficient, prone to error and more likely prone to repeat work. Therefore, it is vital that a modern, interconnected tool suite, be embraced by everyone in the ecosystem, to support the full set of engineering activities across the lifecycle: requirements analysis and management, design, analysis, production, verification, validation, collaborative authoring, technical review, configuration management, maintenance and upgrade, etc. Everyone must have access to the correct information, complete with background and rationale, in context and in a timely manner whilst security and commercial integrity are maintained. The increased use of standard exchange protocols such as Open Services for Lifecycle Collaboration (OSLC) within engineering tools allows data exchange and traceability to occur and therefore allow efficient and consistent use of data across all engineering teams. It is also important for the toolset used in the modelling work to have functionality to track the model history, trace information to its source and rollback changes to earlier points in time.

Variability Examples

Given this general claim the following are offered up as a limited set of examples of where the use of variability modelling alongside the system model may provide benefit:

1. Supporting trade studies

Trade studies have traditionally been conducted outside of the system modelling environment utilizing spreadsheets, simulations and product data sheets to support the engineer in their determination of the best solution to meet the requirements. If conducted in isolation from the wider submarine design, it is possible for the best ‘local’ solution to not be the best overall solution when integrated in to the wider submarine context. The addition of Variant Points within the system model of the submarine, coupled with traditional spreadsheets and simulations, allows the trade study to take account of the wider impact the specific system/sub-system options have on the overall design and help the design team to work within the constraints of the submarine to optimize the design. The use of the system model also allows for additional studies to be conducted where elements from a less preferred option could be incorporated in the best option to benefit the overall solution while preserving all options for future consideration.

Variant Points within the system could be used to ensure the dependencies and exclusions (where identified) are included in the decision process as well as providing the design teams with baseline points should they need to reverse their decision at a later point. The earlier in the design process, the more difficult the dependencies and exclusions will be to identify because less will be known about each individual major system. The Variant Point can therefore be used to record the assumptions made as well as the rationale for the path chosen. This information has been traditionally collected and filed away in isolation but the inclusion of Variants and Variant Points in the model provide the design team with ready access to pertinent information when required through the course of the submarine lifecycle.

2. Planning system updates and technology insertions during major maintenance periods

The use of a system model including variants allows for forward planning of identified updates and insertions and how they can be accommodated during major maintenance periods therefore informing the design team of the best way to design the submarine to allow efficient and effective maintenance to be carried out through life. The study may also highlight more efficient or effective support arrangements than undertaken with previous classes of submarine. Figure 7 shows an example plan for updates performed during maintenance periods for a generic submarine. As part of the maintenance planning activity the impacts of deferred updates or insertions, their dependencies and exclusions and other relevant considerations can be fully explored prior to the design being finalized. This potentially gives the design team valuable information regarding the through life impact and cost of their design decisions at the individual submarine level, the batch level and even the class level. For instance, the team may decide to delay the introduction of new valve and pump technology until new platform management hardware and software, to make effective use of the new technology, is available. Through the use of variant modelling and variant points they may determine that the amount of work required in a maintenance period, the expected increased reliability of the new technology and the lower power consumption have sufficient benefit to install the new technology from build. Alternatively, the Variant Points can be used to determine the essential and non-essential updates required at each maintenance period in order to maximize the submarine availability, whilst maintaining the overall submarine capability and providing cost effective, on schedule maintenance periods. The impact of deferring updates to later maintenance periods can also be assessed.

3. Planning technology refresh periods

With the in-service life of a submarine being in the region of 30 years, there will be a routine need to refresh significant elements of the major systems on board such as electronics, displays and electrical switchboards. These refreshes can be planned and assessed using Variant Points to investigate the optimal periods for refreshing technology. Variant analysis can be used to determine the critical points in time where these refresh periods need to occur and determine the impacts of varying the time and scope of works at which the refresh occurs. The impacts identified during the analysis could be major (i.e. those impacting the capability of the submarine to successfully complete its mission) or minor (i.e. those that have no negative outcome but delay performance improvements). Today's availability periods are typically estimated as fixed durations of time where a backlog of activity is fitted to the schedule. With these techniques, alternative approaches may yield shorter, more frequent availability periods or more likely, a mix of alternate duration and scheduled maintenance intervals which optimize the availability, capability and lifecycle cost of the submarine project. Figure 7 shows the various maintenance periods of the submarine and the associated equipment.

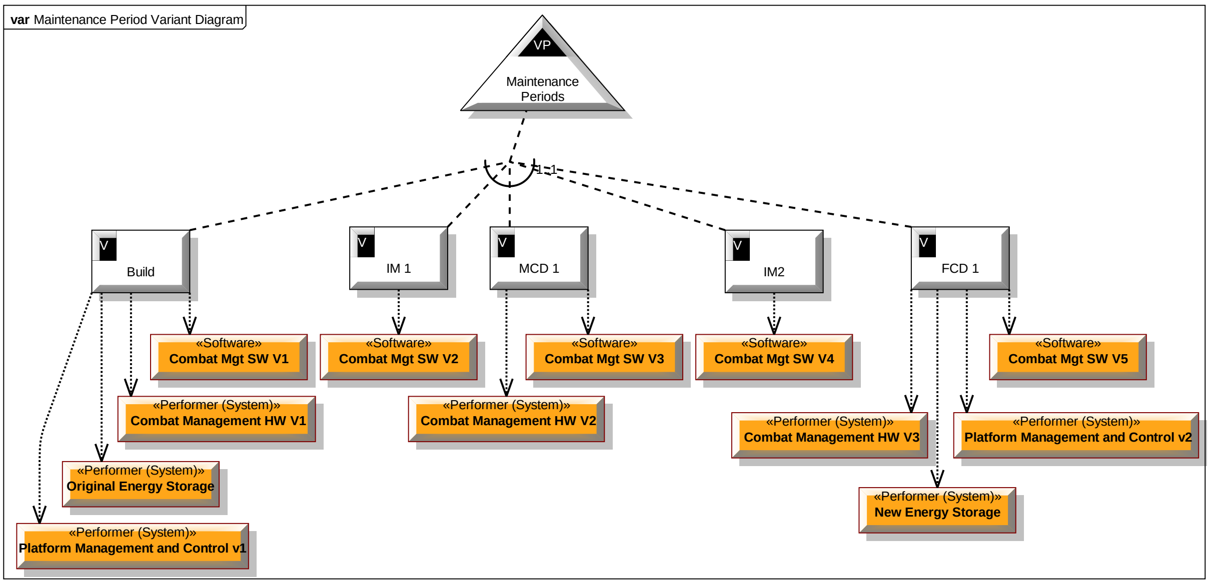

Figure 7. Submarine Maintenance Periods Planned Updates

Variability Selection

Depending on system requirements, different configurations can be chosen to support the mission capability requirements for a specific configuration. Prior to choosing, stakeholders need to decide the different mission, environments, timescales and other options to be included. A variant selector provides a means of choosing the different options that are available. This is a menu-driven interface that provides a means of selecting specific Variants for a Variation Point. For example, the Variation Point in Figure 7 is the Maintenance Period and the Variants are the Build, MP1, MP2, etc. Incompatible choices are also highlighted by the variant selector. For example, if two Variants are defined as mutually exclusive and both are chosen, this is an invalid condition. Having defined the different options, a product model can be generated containing the system elements linked to the selected options. Elements corresponding to Variants that were not chosen are not included in the resultant view of the product model, but are retained in the product family model. Using this product model, trade-off studies can be performed to determine if the selected configuration will meet mission requirements. MB-PLE provides users the best of both worlds – in the same model they can maintain the baseline while considering options simultaneously without the need to work a separate model to focus on the detailed matter being considered. On top of that, the technique enables all of the analysis inclusive of the chosen option to be preserved in context.

Variability modelling post build

The use of variability modelling is not restricted to the design phase. There are major opportunities to utilize variability analysis and variant modelling during the in-service phase of a submarine's life. The in-service phase for each submarine is likely to be at least 30 years. Change in political thinking, military need and technology will require the submarine to be adapted over its lifetime to address the challenges posed by these changes. The use of variant analysis during design provides some assurance that the design is adaptable to change through the submarine's life. However, all changes cannot be foreseen well enough to ensure no new variant analysis will be required throughout the submarines operational life. In fact, this is to be expected and should be designed into the project and by extension the model. MB-PLE enables this approach. As operational experience is gained with the submarine, data is collected on aspects such as performance, reliability, maintainability and usability of the whole submarine and each system on board. This valuable data can also be synchronized back into the model to improve the model and subsequent decision making. Today's techniques do not offer such holistic opportunities. To safeguard the integrity of the data and submarine operations the modeling toolset will need to isolate operationally sensitive information from unauthorized users. The following are examples of how variant modelling can be of value during the in-service phase:

1. Re-planning updates and insertion opportunities as operational experience is gained

As operational data becomes available the analysis of updates and technology insertions can be revisited to determine if changes to the plan could result in a more cost effective option. There may be opportunities to alter the sequence of updates and insertions to later periods where the demonstrated performance of the installed items is better than that predicted during design. Alternatively, updates which result in improved performance may need to be brought forward where current performance does not meet operational needs. There may also be a need to defer planned updates for cost saving reasons or because updates and insertions are not available as originally planned. As all of these options represent variants in the system model, the impact of bringing forward or deferring updates and insertions can be assessed in an efficient manner to determine their whole of life impact.

2. Re-planning as reliability data becomes available

The availability of real reliability data means that predicted data contained within the system model can be replaced with actual data and the effectiveness of the maintenance and update program can be re-assessed against the actual values. New variants can be defined to deal with the changes in reliability and the Variant Points analyzed to determine the most effective maintenance and update plan as measured against key performance indicators such as fleet availability, cost and schedule.

3. Planning unforeseen technology insertions

Throughout the life of a submarine new technology emerges that could not have been foreseen during the original design and build. For instance, design teams working on submarines in the 1980s and 1990s would not have predicted the advances in wireless communication, mobile telephone coverage, data storage, displays and LED lighting that are now available. These advances bring many advantages to the management of weight and power margins on the submarine, and even affect crew morale. Therefore, the maturity of all of these technology options also represents an opportunity to be modelled as a series of options/variants. Utilizing the variants contained within the system it is possible to determine how best to utilize and introduce these technologies to get the biggest capability gains across the submarine fleet at the appropriate cost and risk.

Figure 8 shows an example forecast of the availability of major submarine systems. The different systems are linked to projected timeframes. When considering future submarine configurations, the engineer can determine when the equipment will be available for deployment. When schedules are delayed, the impact on the submarine's capabilities can be assessed and the engineer can plan to take an alternative course.

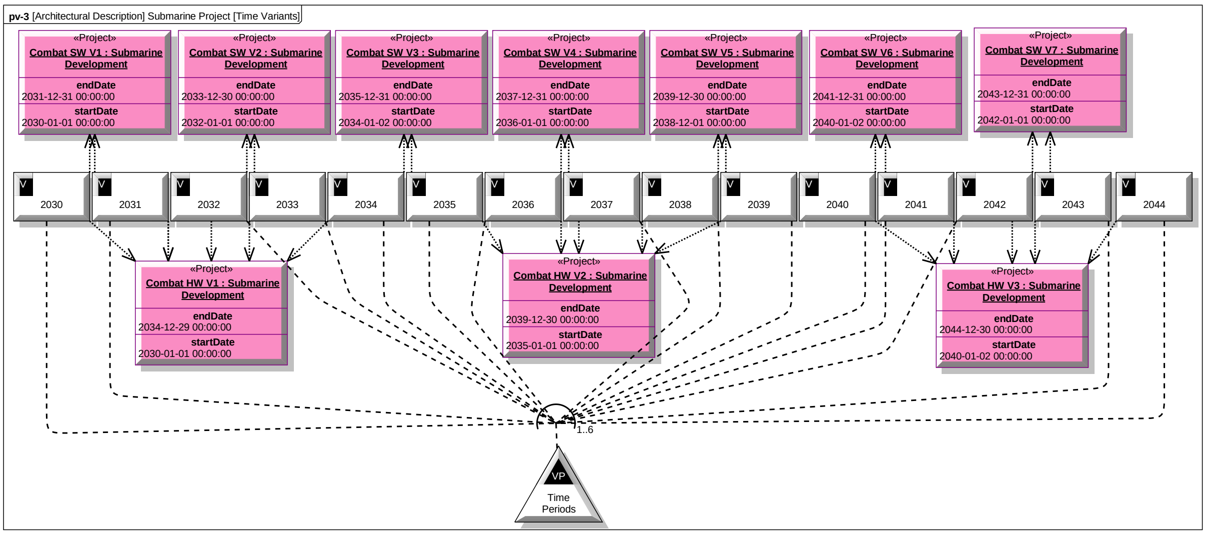

Figure 8. Project to Time Variant Mapping

The submarine variant through life

Taking Submarine 4 of the class allows an example of how the previously described system and variant modelling techniques could be applied throughout the life of an individual submarine. Submarine 4 is the first submarine of the second batch of submarines to be designed and built. The second batch of submarines have additional and improved capabilities over Batch 1 submarines coupled with newly available technology upgrades and the lessons learnt from the build and testing of the first submarine and the ongoing builds of the second and third submarines. Figure 9 shows a simple model demonstrating the relationships between Submarines 1 and 4, their relationships to the different batches and their first major upgrades.

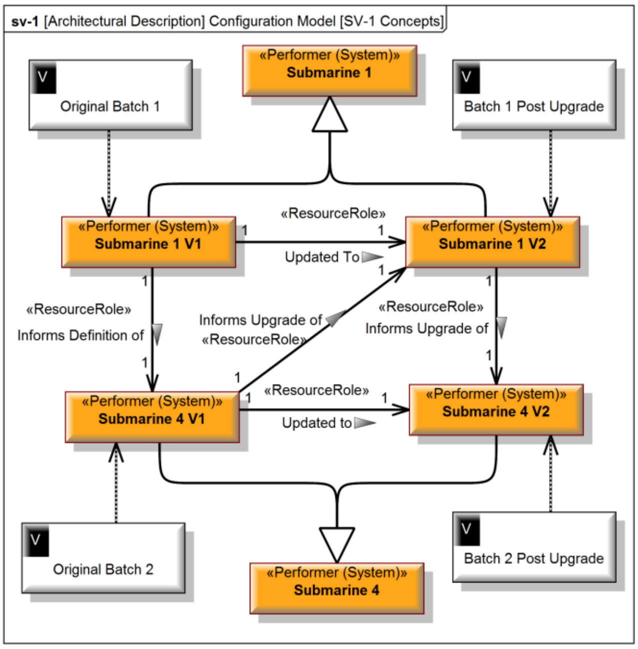

Figure 9. Submarine Variants

The main differences between the Batch 1 and Batch 2 submarine are:

- Capability upgrade – dedicated autonomous vehicle launch and recovery "hanger".
- Capability upgrade – additional mast mounted ISR sensors.
- Capability upgrade – increased submerged endurance.
- Technology upgrade – Combat System hardware update and newest software version.
- Technology upgrade – Platform Management hardware update and newest software version.
- Lesson learnt – revised machinery room layouts for more efficient installation and maintenance.
- Lesson learnt – modified electrical cable routes to allow more efficient installation.

Using the Batch 1 design as the baseline, a set of variants is modelled for the capability upgrades and lesson learnt. The technology update variants are part of the larger planned update program and have been included within the Batch 1 design baseline. Each of the capability updates have a number of solutions that could meet the requirements set for those updates and therefore trade studies will be required to be conducted by the teams generating the design modifications. Each option will be included within the system model and suitable variants including dependencies and exclusions, defined and assessed. As part of the conduct and recording of the trade studies SysML Parametric diagrams will be constructed and linked to any specialist engineering tools such as Mathcad™, Flowmaster™, or Paramarine™ required to undertake detailed analysis of the proposed solutions. The specialist analysis and the analysis of the impact of the variants on the whole submarine over the whole life of the submarine via the system model combine to determine the solution to take forward and provide understanding of the design modifications required to implement the new capability.

The variants defined for the lessons learnt items have less options associated with them than the capability updates as it is likely that only the original and proposed solution will be modelled. The impact that the proposed solution may have on other layout aspects of the submarine or the overall submarine performance can be determined and modifications to the proposed solution made as required until conflicts are resolved. The use of the system model allows holistic analysis of all the proposed changes on the submarine to be easily vetted against the impact to the physical (3D-CAD) design. This has the potential to save time where clashes or performance degradations are identified and resolved prior to expenditure of costly 3D model and production instruction updates.

After all the build related variants have been assessed and final solutions have been confirmed the through life variant points can be explored to determine the detailed variations expected for Submarine 4 during its life and the maintenance points where those variants will be implemented. The parallel development lines for items such as the combat management system hardware and software and the planned maintenance periods will be brought together to determine all variant options for Submarine 4. Trade studies across the available options will be conducted to determine the priority order for updates during for each maintenance point. It should be noted that although hardware and software updates may be available for installation the budget will be used to determine how many of the updates will be implemented and which will be deferred or overlooked. As each maintenance period is conducted through the submarines life the variant options will be reviewed and new priority lists generated to ensure that Submarine 4 provides the required operational capability.

APPLICATION TO OTHER DOMAINS

This is a powerful tool for managing and deploying system configurations though time. These techniques could also be applied to domains other than defense. Rail networks continually evolve and accommodate upgrades to locomotives, passenger and freight cars, and changes in the interaction of users of the systems. Smart Cities are rapidly evolving with a bevy of sensors monitoring the denizens and other agents acting in the system. MB-PLE is applicable to examine every aspect of a smart city. Mining operations run for numerous years to extract minerals from the Earth. The technology advances and customer changes are resulting in operations and automation increasing in levels of complexity and dependency. All of these activities have two things in common – they are complex and they live for very long periods of time.

CONCLUSION

Advances in computing power and the advent of System Modelling methodologies and standards (SysML, MBSE, MB-PLE) have converged providing the opportunity for communities of people to model large scales systems of systems and the evolution of these systems through time. These advances have allowed people to simultaneously consider scenarios at all levels of detail and abstraction and preserve these options in a consistent modelling framework across organizational boundaries. Still further opportunities exist to explore the applicability of MB-PLE modelling techniques on the way people, organizations and now even agents interact with these systems through their development lifecycle and operational use. Qualifying the applicability of these techniques on a system with the size, scale and complexity of a submarine and its extended ecosystem provides ample reference for the use of these techniques in more mundane circumstances in everything we touch each day – mobile phones, televisions, automobiles, and more. Soon these daily systems we all interact with will advance to also interact with each other in a system of systems context creating ever more opportunities to explore optionality/variability to right size each experience to the individual consumer's preference.

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BIOGRAPHY

Matthew Hause is an Engineering Fellow at PTC, the co-chair of the UPDM group and a member of the OMG SysML specification team. He has been developing multi-national complex systems for almost 35 years. He started out working in the power systems industry and has been involved in military command and control systems, process control, communications, SCADA, distributed control, and many other areas of technical and real-time systems. His roles have varied from project manager to developer. His role at PTC includes mentoring, sales presentations, standards development and training courses. He has written a series of white papers on architectural modelling, project management, systems engineering, model-based engineering, human factors, safety critical systems development, virtual team management, systems development, and software development with UML, SysML and Architectural Frameworks such as DoDAF and MODAF. He has been a regular presenter at INCOSE, the IEEE, BCS, the IET, the OMG, DoD Enterprise Architecture and many other conferences.

Jon Hallett has recently joined Shoal Engineering as a Principal Systems Engineer. Prior to this he was a Principal Systems Engineer within the ASC Chief Engineer's Group based in Adelaide, South Australia. He had been reviewing and maintaining the Engineering Management Framework and defining and developing the associated Systems Engineering skills and tools required to support future projects. His previous role in ASC was as the Principal Development Engineer within the submarine design capability, Deep Blue Tech, where he was responsible for developing the systems engineering products and processes required during design and production support. Prior to joining ASC in 2008 he had gained 23 years of defence experience having worked for QinetiQ in the UK, where he led maritime defence related research and development teams and led business unit and divisional level systems engineering development activities. He has also been a self-employed consultant providing maritime mine warfare and systems engineering advice and support to the Finnish Navy. Jon is a Certified Systems Engineering Professional, has a Master of Engineering in Military Systems Integration from the University of South Australia and a Bachelor of Science from Aston University.