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Modeling the Evolution of a System Over Time

Matthew Hause
PTC
Engineering Fellow and GTM Solutions Specialist
3208 Misty Oaks Way
Round Rock, Texas, 78665
MHause@PTC.com

ABSTRACT

Systems change over time. Sometimes this is planned as in the normal maintenance, planned upgrades, refits and modifications to keep a system fit for purpose and ready to deploy. There may also be multiple allowable configurations of a system providing flexibility to meet different operational needs. Sometimes the changes are not planned. This can be due to complete system failure, component failure, accidental or deliberate damage, as well as unforeseen operational needs. Whatever the reason for the change, the "To-Be" configuration of the system needs to be captured, analyzed and evaluated to ensure it will meet the projected operational need. Systems engineering and trade-off analysis also need to be performed to ensure that the best configuration of the system has been specified regarding time, cost, system effectiveness, as well as a host of other criteria. Additionally, it is not sufficient to simply model the system configurations. It is necessary to show how a configuration will evolve over time, how the variations will differ, common components, additional and emergent behavior, how a systems behavior and capabilities change over time, etc. For military vehicles, there is the additional dimension of the configuration of a manufactured set of vehicles. They are traditionally manufactured in this way in order to take advantage of economies of scale, as well as other factors. Over the typical course of a system lifecycle, they are regularly serviced and reconfigured to address operational needs as well as take advantage of technological developments. Mission and usage parameters continually evolve and the vehicle must adapt to suit. These need to be planned in advance, and the multiple configurations of each vehicle or set of vehicles need to be tracked and managed. No two vehicles are the same and arguably no two systems of systems are the same. This paper will show how these configurations can be modeled, managed and analyzed in an effective way.

INTRODUCTION

The life of a class of military ground vehicles can be measured in decades. As such the operational demands and expectations change both strategically and tactically over its lifetime. Traditionally this has been accepted as the case and in most cases requirements and design have been managed via the configuration management team at a class or batch level. 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 vehicle 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, or any combination thereof can be modified over time. There are too many ground vehicles to do so at the individual level, but lessons can be learned at the class of vehicle and the batch in which they are manufactured. 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 a ground vehicle's configuration over time in the context of the class, whilst simultaneously highlighting the wider application in the enterprise and beyond.

The Big Picture

As a major military asset military ground vehicles, and the enterprise operating and supporting them, need 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, they must deal with tactical changes (different weapon configurations, sensors or countermeasures) as well as equipment defects and failures. 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. The configuration of a class of vehicles has been managed in terms of agreed changes against the class or batch baseline. This has resulted in much of the knowledge being retained solely among senior staff or only obtainable by examining specific vehicles to determine its actual layout and configuration. Lessons learned, problems found in the field, component failures, maintenance problems and other issues can also be lost.

Advances in technology (hardware performance, software tools and standards) now give us the opportunity to not only manage vehicle configurations and requirements 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, or any combination thereof can be modified over time (proactive management through analysis and planning). Due to the complexity of a military ground vehicles and their 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 provides an agile means of evaluating alternative configurations. PLE allows the definition of variants at any level of abstraction or level of detail in measures of time, and different configurations for both time scales and mission purpose. This paper will show how PLE/OVM can be used to improve MBSE (MB-PLE) for systems with specified characteristics (long life-spans, volatility in requirements/political and social need, etc.). Specifically MB-PLE will provide a means to plan, track, manage and evaluate a configuration over time in the context of the class, whilst simultaneously highlighting the wider application in the vehicle enterprise and beyond. [10]

Model-Based Systems Engineering (MBSE)

These days more often than not, the configuration definition and management and the subsequent systems engineering and analysis are conducted using Model-Based Systems Engineering techniques (MBSE). The state of the art language for supporting these activities is the Systems Modeling Language (SysML). For systems of systems (SoS) this is done using the Unified Profile for DoDAF and MODAF (UPDM). UPDM implements the Department of Defense Architecture Framework (DoDAF), the Ministry of Defence Architecture Framework (MODAF) and the NATO Architecture Framework (NAF) using SysML. [1], [11] This provides a means of performing systems engineering on the SoS rather than simply capturing the architecture as a collection of models. Recent versions of UPDM architectures can now take the fourth dimension (time) into account. The paper "Architecting in the Fourth Dimension - Temporal Aspects of DoDAF" by [3] captures many of these aspects. However, the management of the configurations, assembly of them, analysis and engineering and generation of variations of the configurations requires additional techniques. This is provided by 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. [2], [9] By defining the systems as abstract blocks, trade-off analysis can take place at a higher level of abstraction saving time and more quickly eliminating unworkable configurations.

Example Vehicle Description

For the purposes of this paper, a simplified class of generic military ground vehicle 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. The simplified generic vehicle will consist of the following major systems, as shown in Figure 1:

- Power Subsystem
- Lighting System
- Brake Subsystem
- Chassis Subsystem

- Body Subsystem
- Comms Subsystem
- Navigation Subsystem
- Interior Subsystem
- Vehicle Armor
- Surveillance Subsystem
- Weapons Subsystem
- Tactical C4 System

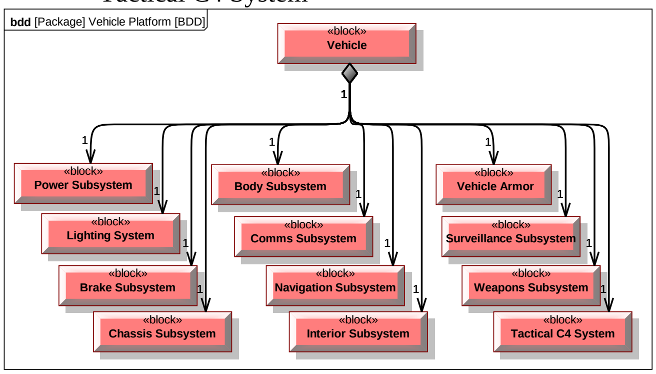

Figure 1. Major Vehicle Systems

For simplicity, this paper will concentrate on only a few of these systems. Each batch of vehicles will have different capability requirements and detailed design. Each vehicle within a batch will have the same "build to" design but will incorporate lessons learnt during the construction and integration of earlier vehicles and the available updated hardware and software components to the extent that the "as built" of each vehicle, even within a batch, eventually will not be identical. This means that each vehicle 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.

Typical Vehicle Lifecycles

The lifecycle of ground vehicles varies greatly depending on the type of vehicle, configuration, environment, usage, mission type, etc. It is useful to give some examples from the Military Equipment Useful Life Study - Phase II Final Report created by the Office of the Under Secretary of Defense (Acquisition, Technology and Logistics), Property and Equipment Policy Office and Office of the Under Secretary of Defense (Comptroller), Accounting and Finance Policy Office issued May 30, 2008. [12] The first example is the Combat Vehicles - Army and Marine Corps M1A1 Abrams Main Battle Tank. The Abrams Main Battle Tank has three usage-based service life limiters: miles driven, engine hours, and equivalent full charges/rounds fired from the gun tube (EFCs). The hull may last indefinitely, and components are replaced and upgraded through maintenance and recapitalization activities as needed to maintain operational capabilities. Therefore, the service life of the tank is defined as the amount of usage that can be expended before a recapitalization or rebuild is required, as defined by the PMO and tank rotational guidance (e.g., Marine Corps Combat Vehicle Evacuation Program). The primary usage driver is mileage since the tank typically reaches the mileage limit prior to reaching the hours or EFC limits and should be the basis of service life for analysis in the methodology. The Army Abrams Main Battle Tank has an engineering-based service life of 6,000 miles, and the Marine Corps Abrams has a service life of 3,000 miles.

The second set of examples are Tactical Vehicles - Army M1151 HMMWV, Marine Corps M1114 HMMWV, and SOCOM GMV. The HMMWV has a design service life of 45,000 miles. Historically, the programmed usage in a peacetime environment under normal use was approximately 3,000 miles per year, which resulted in a 15-year [45,000 / 3,000] useful life for the vehicles. The HMMWV and GMV programs, specifically the M1114 and M1151 HMMWV variants, have experienced a significant increase in utilization over programmed estimates as a result of GWOT operations, at a rate of two to five times the programmed estimates. GWOT has resulted in some vehicles reaching 3,000 miles in one month. The M1114 and M1151 vehicles have also been configured with retro-fit capabilities that have pushed the vehicles to operate above their design gross vehicle weight limit specifications. This has resulted in increased stress and structural fatigue.

Consequently, the maintenance schedules of the vehicles will vary depending on the usage of each individual vehicle. This includes the configuration, environment, mission usage, total hours used, total miles travelled, etc. This will have the greatest impact on the mechanical systems, although electronics will be affected as well.

Example Vehicle 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 vehicle. Each batch will have a different initial capability and technology baseline. Within each batch each vehicle will have the same basic capability and "build to" design; batches of vehicles will be delivered (built) at 2 year intervals. In parallel to the vehicle design, construction and maintenance efforts the following major systems will be undergoing significant development and enhancement throughout the vehicle lifecycle. For the example, the Tactical C4 system will be used. This consists of a HW and SW component. The SW is updated more frequently than the HW and each is on its own development lifecycle. There are dependencies between the systems as well in that some newer versions of SW cannot run on older versions of HW. This is typical in computer systems.

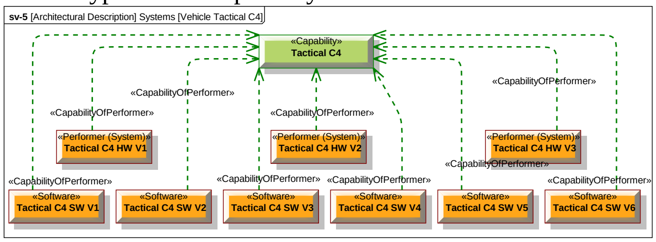

Figure 2. Tactical C4 Systems HW and SW

Figure 2 shows the Tactical C4 Systems Hardware and Software systems and their supporting relationships to the Tactical C4 capability. The Capability of Performer relationships indicate that these systems and software support or implement the Tactical C4 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 Tactical C4 system and software throughout the life of the vehicle class.

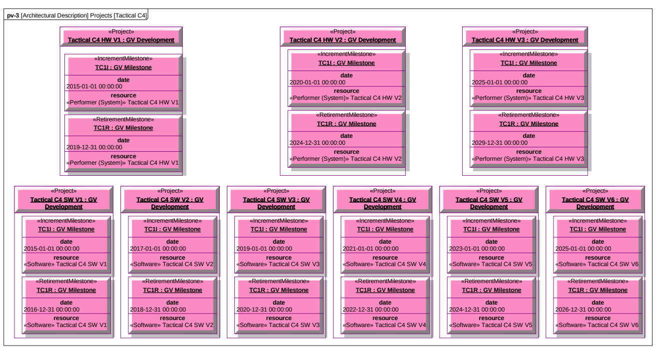

Figure 3. Tactical C4 HW and SW Projects and Milestones

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 Tactical C4 System. It is important to point out these diagrams are automatically generated based on the data and relationships authored in the model.

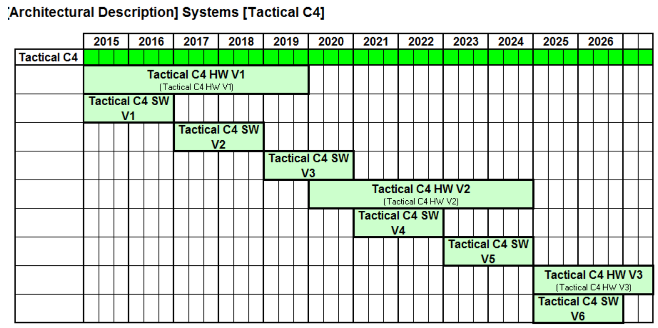

Figure 4. Tactical C4 HW and SW

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 [6], [7] and is now an ISO standard (ISO 26550: 2013, Reference Model for System and Software Product Line Engineering and Management). Through this modeling technique, product line engineers have the ability to design product line variability options, constraints and conflicts, (if any exist), and to pick their desired end product by deciding on the variability options. Using an automotive example, the variation point might be car color and the variants could be gray, green and blue. A more complex variation point would be a combination of engine types, transmission types and the definition of compatible configurations. [4]

Variant Modelling

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 Variation 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.

Product Models

After modeling 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. In addition to the physical configurations, this can also capture performance metrics, requirements, capabilities, functional specifications, scenarios, and so forth. Individual configurations can then be generated as product models. Typical system engineering activities such as trade-off analysis can be performed on these product models to ensure the system is fit for purpose. When problems with components are found in the field, configuration changes can be made and impact analysis evaluated. This provides significant benefits for engineers trying to capture and demonstrate the different configurations of the system.

Use in Vehicle Design

For vehicles, 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 vehicles and the evolution of each vehicle batch over time. Variation Points would be added for each batch in addition to time. In the case of a vehicle, an example of a simple variation point might be Mission Type and the variants could be Search and Rescue, peace Keeping, Combat and Interdiction as shown in Figure 5. 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. Any combination of the various options can be selected, with a minimum of 1 and a maximum of 4.

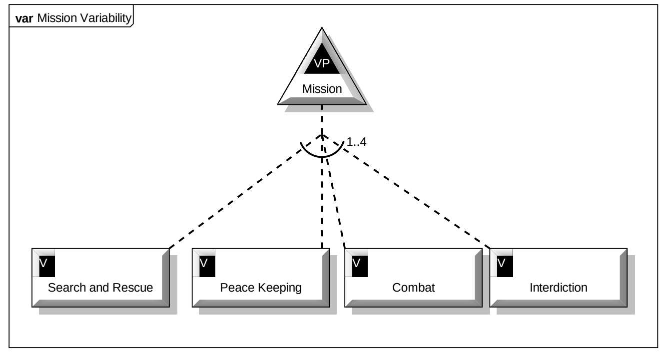

Figure 5 Mission Variability

A more complex example of a variation point is a combination of Environment and Humidity types as shown in Figure 6

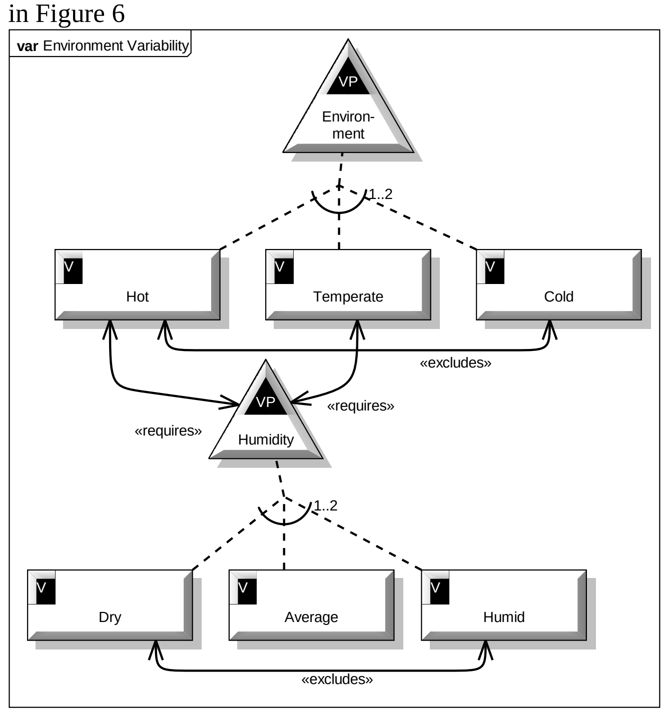

Figure 6 Environmental Variability

Figure 6 shows a more complex example of the notation. The environment can be hot, temperate or cold. A maximum of two can be selected, but not both hot and cold shown via the “excludes” relationship. If hot or temperate are selected, then humidity must also be selected. Again, a maximum of two can be selected, but dry cannot be chosen as well as humid. 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 vehicle, batch, and class levels. This provides significant benefits for engineers trying to capture and demonstrate the different configurations of the system and allows cost effective, lower risk options for the ground vehicle project as a whole to be identified. After modelling the variability in the product line model, the engineer can then 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.

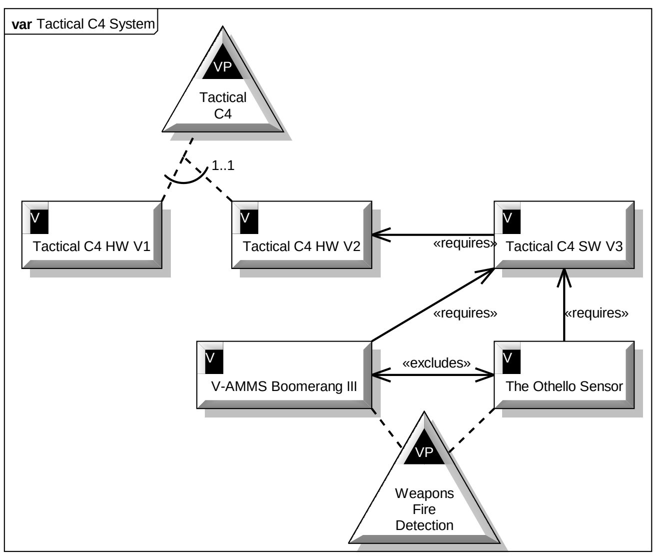

Figure 7. Combat Systems Variants

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, Activities, 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 8.

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.

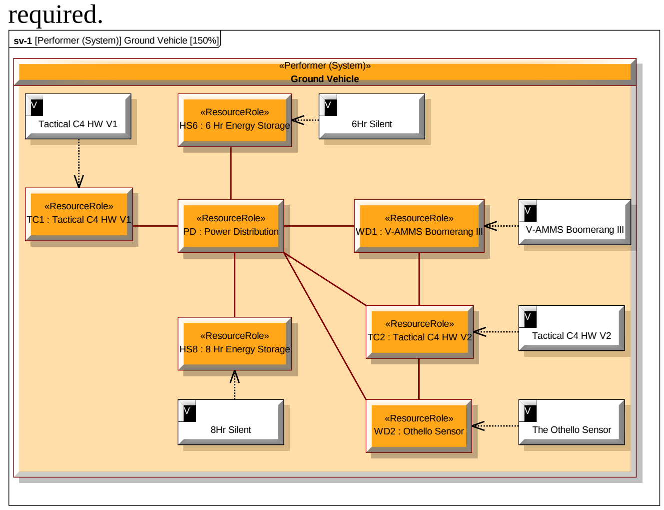

Figure 8. Vehicle 150% Model

Variation and Dependency Modelling are key concepts frequently encountered in vehicle design. Today, these factors are manually managed. Figure 8 shows an example of 150% Model of a vehicle. In this example there are two different Tactical C4 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 9, 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 vehicle there are many points where options are studied and decisions made about the design. Engineers traditionally record 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 vehicle 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 many design teams on modern military platforms, 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 vehicle's lifecycle. This makes the future design, maintenance and upgrade of the vehicle 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.[9] 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, simulation, physics-based tools 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 vehicle design, it is possible for the best 'local' solution to not be the best overall solution when integrated in to the wider vehicle context. The addition of Variant Points within the system model of the vehicle, 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 vehicle 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 vehicle lifecycle. SysML rationale elements can also be used to record the result and reasoning behind decisions.

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. This forward planning informs the design team of the best way to design the vehicle to allow efficient and effective maintenance to be carried out through life. The study may also highlight more efficient or effective support arrangements than those undertaken with previous classes of vehicle. Figure 9 shows an example plan for updates performed during maintenance periods for a generic vehicle. 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 vehicle level, the batch level and even the class level. For instance, the team may decide to delay the introduction of new 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 vehicle availability, whilst maintaining the overall vehicle 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 vehicle being in the region of 10-20 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 vehicle 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 vehicle project. Figure 9 shows the various maintenance periods of the vehicle and the associated equipment.

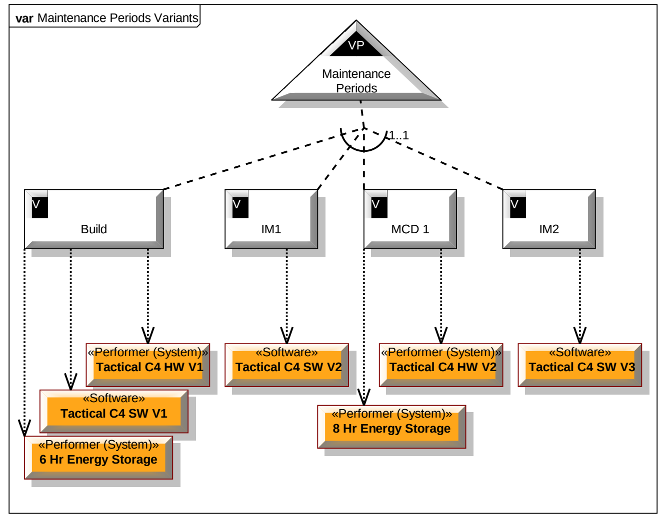

Figure 9. Vehicle Maintenance Periods Planned Updates

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 9 is the Maintenance Period and the Variants are the Build, IM1, MCD1, IM2, 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 Modeling 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 vehicle's life. Change in political thinking, military need and technology will require the vehicle 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 vehicle's life. However, all changes cannot be foreseen well enough to ensure no new variant analysis will be required throughout the vehicles 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 vehicle, data is collected on aspects such as performance, reliability, maintainability and usability of the whole vehicle and each system. 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 vehicle 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 reliability data based on trials and missions 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 vehicle new technology emerges that could not have been foreseen during the original design and build. For instance design teams working on vehicles 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 vehicle, 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 vehicle fleet at the appropriate cost and risk.

Figure 10 shows an example forecast of the availability of major vehicle systems. The different systems are linked to projected timeframes. When considering future vehicle configurations, the engineer can determine when the equipment will be available for deployment. When schedules are delayed, the impact on the vehicle's capabilities can be assessed and the engineer can plan to take an alternative course.

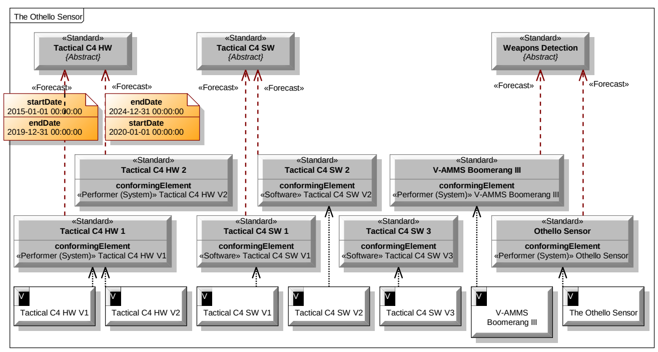

Figure 10. Project to Time Variant Mapping

The vehicle variant through life

Taking Vehicle Batch 1 (including variants) of the class allows an example of how the previously described system and variant modelling techniques could be applied throughout the life of a vehicle batch as shown in Figure 11.

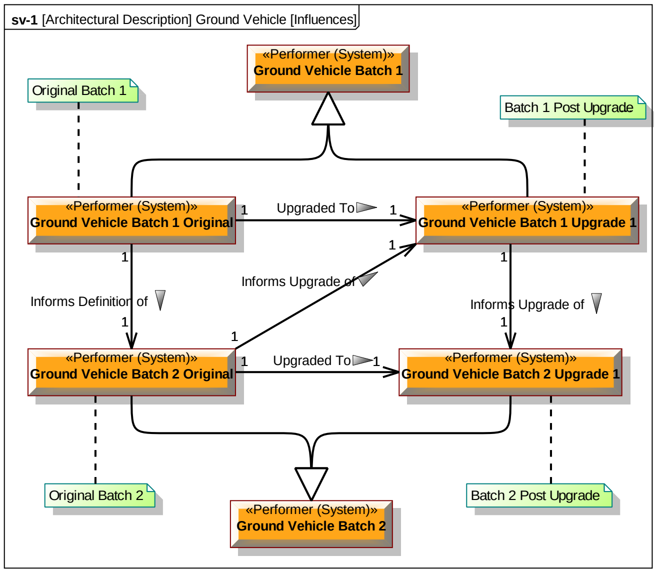

Figure 11. Vehicle Variants

Vehicle Batch 1 is the first batch of vehicles to be designed and built. The second batch of vehicles have additional and improved capabilities over Batch 1 vehicles coupled with newly available technology upgrades and the lessons learnt from the build and testing of the first vehicle batch and the ongoing builds of the second and third vehicles. Figure 11 shows a simple model demonstrating the relationships between Vehicle batches 1 and 2, and their first major upgrades. The main differences between the Batch 1 and Batch 2 vehicle are:

- Capability upgrade – increased silent running
- Technology upgrade – Tactical C4 hardware update and newest software version
- Technology upgrade – Platform Management hardware update and newest software version
- Lesson learnt – revised 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 lessons 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™, or Simulink™ required to undertake detailed analysis of the proposed solutions. The specialist analysis and the analysis of the impact of the variants on the whole vehicle over the whole life of the vehicle 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 vehicle or the overall vehicle 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 vehicle 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 Vehicle Batch 1 during its life and the maintenance points where those variants will be implemented. The parallel development lines for items such as the Tactical C4 system hardware and software and the planned maintenance periods will be brought together to determine all variant options for Vehicle Batch 1. 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 vehicle's life the variant options will be reviewed and new priority lists generated to ensure that Vehicle Batch 1 provides the required operational capability.

Application to Other Domains

The techniques described in the paper are powerful tools for managing and deploying system configurations over time. These techniques could also be applied to domains other than defense where it is necessary to show configurations over time. Rail networks continually evolve and accommodate upgrades to locomotives, passenger and freight cars, and changes in the interaction of users of the systems, and infrastructure systems showing project phases. Smart Cities are rapidly evolving with a bevy of sensors monitoring the drivers, passengers, transport systems 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. In fact, these techniques are applicable for any modeling exercise where the "as-is" and the "to-be" systems need to be demonstrated. 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 exist for 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 class of military ground vehicles and their 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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