2015 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
SYSTEMS ENGINEERING (SE) TECHNICAL SESSION
AUGUST 4-6, 2015 – NOVI, MICHIGAN

Using Model-based Product Line Engineering for Decision Making and to Guide Product Development

Matthew Hause
Andreas Korff
Hedley Apperly
PTC
140 Kendrick St
Needham, Mass

ABSTRACT

Product Line Engineering (PLE) is the engineering and management of a group of related products using a shared set of assets and a means of design and manufacturing. PLE can include system and software, assets and involves all aspects of engineering including electrical, electronic, mechanical, chemical, etc. PLE is normally considered after the product has evolved and complexity becomes too much to manage. Leveraging PLE from the very beginning will identify cost savings and commonality and provide a natural means for product evolution. Orthogonal Variability Modeling (OVM) provides a natural decision set allowing engineers to perform trade-offs for specific customers and guide system development along the most effective route. Using automotive examples, this paper will describe Model-based Product Line Engineering, the process for creating product lines, and the benefits of this approach as applicable to the military ground vehicle domain. Finally, it will show how the adoption of MB-PLE early on in the development lifecycle provides more benefits without the potential disruption and re-engineering that can be involved when it is adopted later on in the lifecycle.

INTRODUCTION

Product Line Engineering (PLE) is the engineering and management of a group of related products using a shared set of assets and a means of design and manufacturing. PLE can include both software and system assets and involves all aspects of engineering including electrical, electronic, mechanical, chemical, etc. As this whole of system approach is also essential for systems engineering, PLE is becoming more relevant to systems engineers. Model-Based Systems Engineering (MBSE) at the enterprise level using architecture frameworks such as DoDAF [1], and the systems level using the Systems Modeling Language (SysML) [2, 3] is now becoming the norm in the industry. The recent International Council on Systems Engineering International Workshop and International Symposium contained a large number of submissions on MBSE in a wide range of industries. This trend has been growing over the past 20 years and will continue to grow. In addition, PLE is being investigated particularly in the automotive arena, but also in rail, power systems, manufacturing and MBSE in general. These are all industries looking to adopt PLE and leverage the capabilities to achieve economies of scale and drive down product costs.

Traditionally, product lines evolved over a period of time. Manufacturers would create a single product for a specific purpose or customer. Variations of the product would be created when customers' needs changed or to improve production. Eventually, these would evolve into product lines. However, creating the product lines after the fact takes considerable time, money and effort to achieve the return on investment. It can involve re-engineering the systems to identify and capitalize on the product lines and can disrupt development schedules. A different approach is necessary. Systems engineers start by examining the whole product as well as the whole of product life cycle. [6, 9] They also need to consider the evolution of the product line, potential variants, evolving technologies, future customer features, etc. from the very beginning. Leveraging PLE early on will identify cost savings and commonality and provide a natural means for product evolution. Applied early on in the process, Orthogonal Variability Modeling (OVM) will also provide a natural decision set allowing engineers to perform trade-offs for specific customers and guide system development along the most effective route. [5, 7]

In this paper, we will first examine some of the available techniques for MBSE and PLE and how they provide Model-based Product Line Engineering (MB-PLE). Next we will look at how OVM provides a decision hierarchy. Using automotive examples, this paper will describe Model-based Product Line Engineering, the process for creating product lines, the 150% model, variant modeling, mapping variation systems, variant feature selection, product model creation, and the benefits of this approach as applicable to the military ground vehicle domain. Finally, it will show how the adoption of MB-PLE early on in the development lifecycle provides more benefits without the potential disruption and re-engineering that can be involved when it is adopted later on in the lifecycle.

MB-PLE and its roots

There are several enabling technologies and standards that enable PLE and MBSE. Orthogonal Variability Modeling (OVM) provides the ability to model systems and software products, their variation points, mutual exclusions, and product dependencies resulting in product lines. OVM was developed by the University Duisburg-Essen, PALUNO Institute and is now ISO standard ISO 26550: 2013, Reference Model for System and Software Product Line Engineering and Management [5]. Through this modeling technique, users have the ability to see their options and conflicts, (if any exist), and to pick their end desired product. OVM can be applied at all levels of the architecture. The OVM notation can be integrated into architecture frameworks such as DoDAF [1], systems architectures using the Systems Modeling Language (SysML) [2, 3], and software architectures using the Unified Modeling language (UML). [4] Traditionally, product lines are created once the complexity of a set of products reaches a point where it becomes too difficult to manage. The various variant architectures and their resultant models corresponding to customers, product variants, phased developments, customizations, etc. multiply to the point that normal techniques are no longer valid. Engineers would then define a product line and its various options by defining a model called the 150% model. This contains the system along with all of its possible system components, interfaces, behavior, requirements, etc. For example, this would define a car as simultaneously having a 4, 6, and 8 cylinder gasoline engine as well as a diesel engine. OVM provides the ability to define a variation point of Engine, and then define that one and only one of the 4 engines above can exist in any actual product. In addition dependencies between engine type and transmission type, exclusive or relationships, etc. can also be defined. Each of these components can be a complex system of systems in and of itself. Often the internal details of these systems are not pertinent or can increase the size of the model. In addition, it is often necessary to reuse the components without changing them. There may be several different versions of evolutions of the systems as well.

Combining MBSE and PLE provides the ability to implement Model-based Product Line Engineering (MB-PLE) at all levels of architecture and throughout the various phases of the development cycle. Adopting an MB-PLE approach impacts the fundamentals of how organizations deliver and compete with their product lines. Adopting MB-PLE early on in the development lifecycle allows the organization to capitalize on the advantages of MB-LPE and leverage the proven ROI of these techniques. It will also provide a decision framework to guide development and ensure the most appropriate product for the market, domain and the customer. The variation points, variants, dependencies and mutual exclusion constructs naturally lend themselves to the decision making process as well as the product specification process. Using a decision execution engine, the engineer can review the results of the decision and perform trade-off analysis. The same techniques can be used for market analysis as well as detailed engineering making the techniques applicable for multiple stakeholders.

Military Vehicle Example

In this example, a new military vehicle is being planned. As part of the requirements solicitation, the stakeholders are specifying the required capabilities, use cases, usage scenarios, operating environments, etc. These include mission types, operating environments, mission length, threats and risks, and so forth. The following example demonstrates the decision sets for the military vehicle. Of course, the total possible variations would be far too many to fit in a technical paper. Therefore, this paper will only document a subset of these. In addition, they reflect generic rather than specific choices.

Variability of Use

The vehicle will have a variety of uses in a variety of environments. We will start with the missions for which the vehicle will be used as shown in Figure 1.

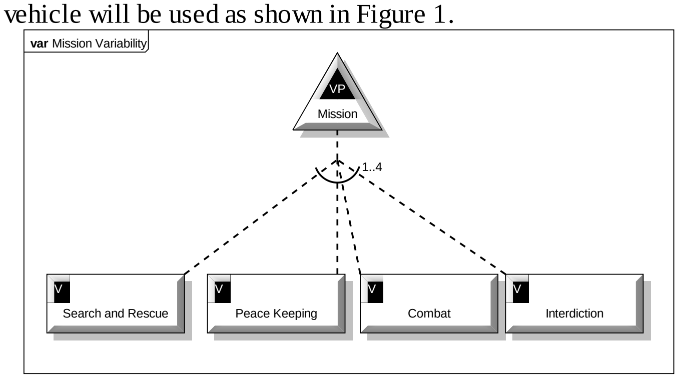

Figure 1. Mission Variability

The triangle notation specifies the variability for missions or different mission types. These include Search and Rescue, Peace Keeping, Combat and Interdiction. From a DoDAF perspective, these missions map to enterprise capabilities that the system will contribute to. In many situations, more than one mission may be necessary for the vehicle. For example, the vehicle may depart on a search and rescue operation and be forced to engage in combat. For this reason, the multiplicity is set to “1..4”. We next define the different environments in which the vehicle can operate as shown in Figure 2.

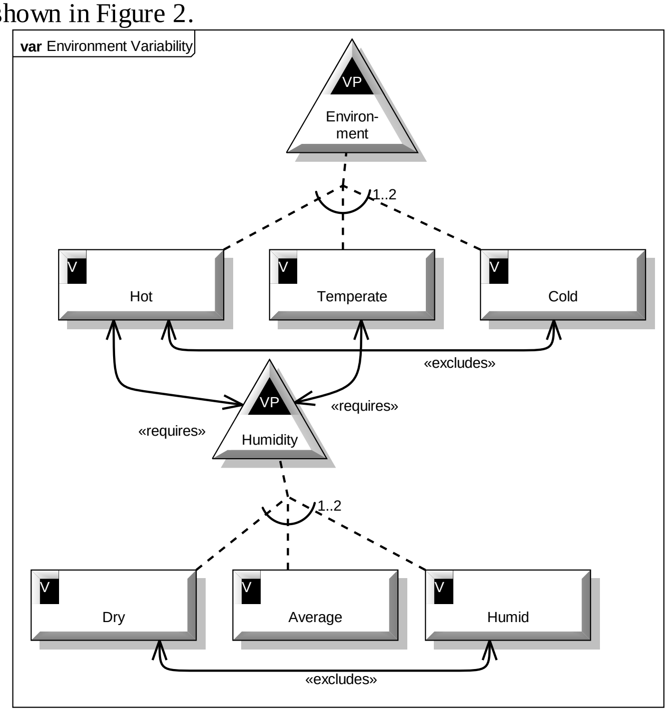

Figure 2. Environment Variability

The choices regarding Environment are more complex resulting in a more complex decision hierarchy. Figure 2 defines possible environments as Hot Temperate and Cold. Only one or two of these environments can be selected. In addition, both Hot and Cold cannot both be chosen. This will reduce vehicle cost, weight and power consumption as outfitting a vehicle for both arctic and desert conditions would require a considerable amount of equipment. For hot and temperate environments, humidity may also be a factor so these point to an additional variation point of humidity. Possible choices are Dry, Average or Humid. These environmental factors will affect vehicle heating and cooling systems as well as modify maintenance procedures and two choices can be made. Again, a mutual exclusion is called for as both dry and humid cannot simultaneously be chosen. Terrain will also affect system structure and are terrain types are defined in Figure 3.

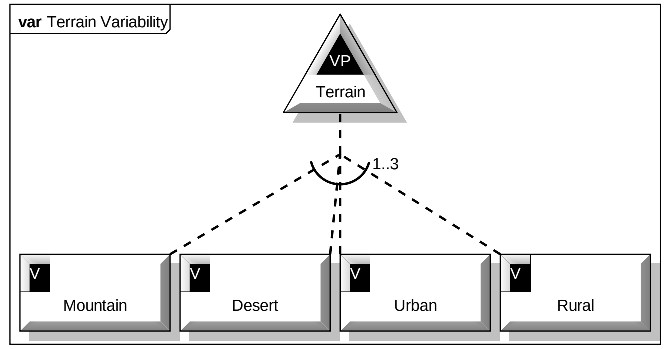

Figure 3. Terrain Variability.

Terrain types are defined as Mountain, Desert, Urban and Rural. Any three of these can be chosen, although the multiplicity at this point is at best a guess. Further evaluation of the necessary equipment and subsequent cost, weight and power consumption might further limit this. This is because each variant will be linked to the necessary equipment necessary to support the variation. Other model elements such as activities, interfaces, use cases, requirements, standards, etc. can also be linked. This is illustrated in Figure 4 detailing light conditions.

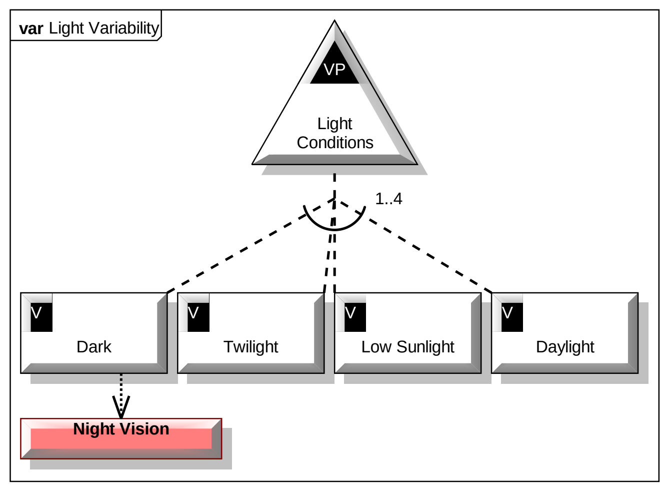

Figure 4. Light Conditions Variability.

Figure 4 describes the various light conditions for the mission. This includes Dar, Twilight, Low Sunlight and Daylight and any and all can be chosen. If Dark is selected, then Night Vision equipment will be necessary as shown. Additional equipment will be linked to the other variants. These variants can also constrain mission parameters as well. Operating in Daylight for example, will make the vehicle more visible and thus more easily targeted. Threat types are listed in Figure 5.

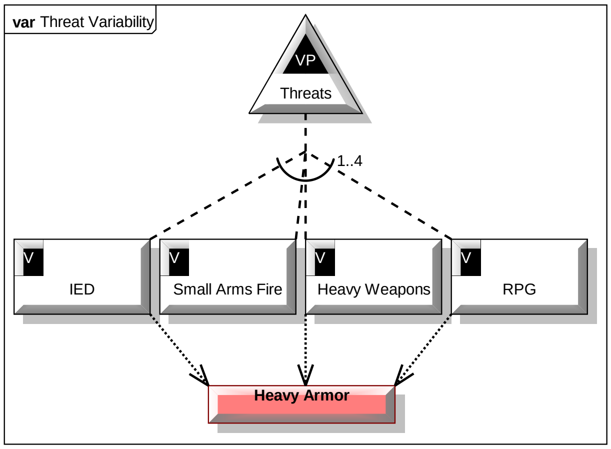

Figure 5 Threat Variability

Of course, other threats can and should be defined. These have been chosen to illustrate that IED, Heavy Weapons and RPG threats will all require that the vehicle be outfitted with heavy armor. As mentioned earlier, other variability options would be developed in the course of the system requirements. Creating and linking variants during design (as part of the design process) means that the options and links are already in place and all you need to do is make decisions. This simplifies the design process considerably and results in a decision and requirements driven design.

System Configuration

Having defined the missions, functional diagrams such as use case diagrams would be elaborated to explore the various usage scenarios. From these, a set of system components would be defined to supports the required activities and scenarios. A vehicle hierarchy of system components is shown in Figure 6.

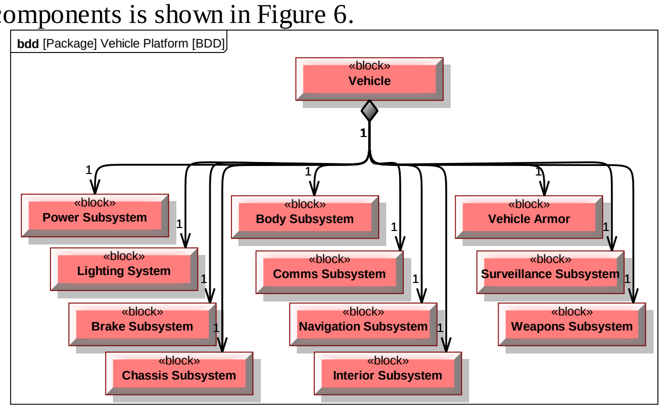

Figure 6 Main Vehicle Subsystems.

Figure 6 details the main vehicle subsystems. Standard vehicle subsystems such as Power, Lighting, Brakes and Chassis are listed in addition to military systems such as Vehicle Armor, Surveillance and Weapons. These are generic systems that will need to be detailed as shown in Figure 7. Initially, these could be logical systems used to specify structural elements that provide functionality. They could also be existing system component such as COTS or GOTS. They could also be stored in an asset library and reused via standards based techniques such as the Reusable Asset Specification. [8]

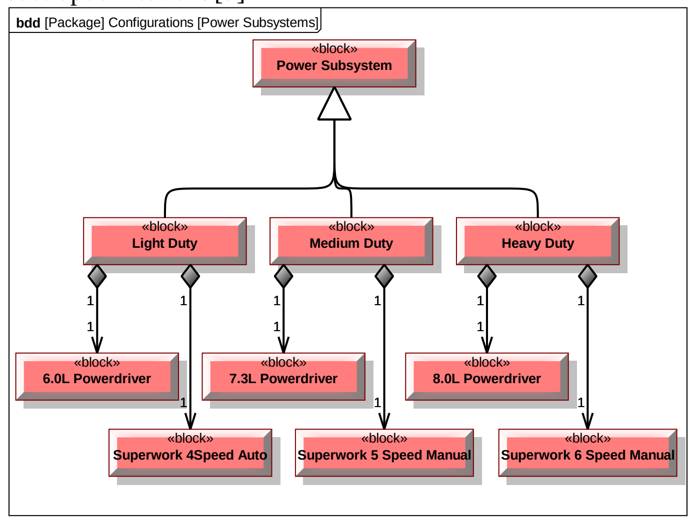

Figure 7 Power Subsystem Configurations

Figure 7 details the Power Subsystem components. Light, Medium and Heavy Duty power systems consisting of different size engines and transmissions are listed. Depending on system power requirements, different configurations can be used to support the vehicle requirements. Prior to choosing, we need to decide the different mission, environments and other options as shown in Figure 8.

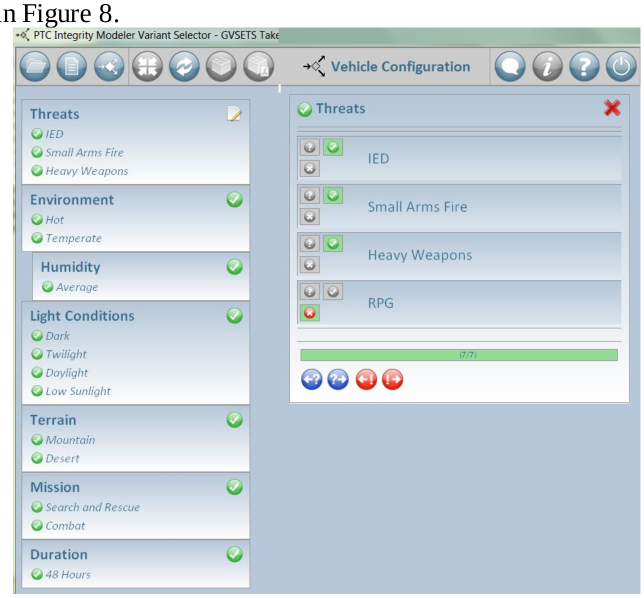

Figure 8 Variant Selector Interface

The variant selector provides a means of choosing the different options that are available. On the left hand side the options that have been selected are shown. The right side shows the threats options where all but the RPG has been selected. Having defined the different options, a product model can be generated containing the system elements linked to the selected options. However, to decide if the configuration will meet mission requirements, trade-off analysis will need to be performed.

System Trade-off Analysis

The required Size, Weight and Power (SWaP) required for the vehicle will vary depending on the configuration. The overall aspect of this will require a set of complex calculations from various system elements. These can be evaluated in a variety of ways. Figure 9 illustrates a SWaP type of spreadsheet.

	Quantity	Mass (in kg)				
		Estimate	Margin (%)	No Margin	With Margin	Budget
Mission (Vehicle Systems::Struc	n/a	0	0.00%	3800	7980	4000
Vehicle (Vehicle Systems::Stru	1	3800	110.00%	3800	7980	4000
Power Subsystem (Vehicle S	1	0	0.00%	0	0	0
Power Control Unit (Vehicl	1	0	0.00%	0	0	0
Fuel Tank Assembly (Vehicl	1	0	0.00%	0	0	0
Differential (Vehicle Syster	1	0	0.00%	0	0	0
Wheel Assembly (Vehicle S	1	0	0.00%	0	0	0
Battery Pack (Vehicle Syste	1	0	0.00%	0	0	0
Brake Subsystem (Vehicle Sy	1	0	0.00%	0	0	0
Body Subsystem (Vehicle Sys	1	0	0.00%	0	0	0
Interior Subsystem (Vehicle !	1	0	0.00%	0	0	0
Navigation Subsystem (Vehi	1	0	0.00%	0	0	0
Lighting System (Vehicle Syst	1	0	0.00%	0	0	0
Chassis Subsystem (Vehicle !	1	0	0.00%	0	0	0
Comms Subsystem (Vehicle !	1	0	0.00%	0	0	0
Weapons Subsystem (Vehicl	1	0	0.00%	0	0	0

Figure 9 SWaP Spreadsheet (Fragment)

In this example, a partial list of parts and the masses of the components are shown. Only some of the system elements have been sized to illustrate the concepts. Other groups of columns could also include Power, Size, Cost and a number of other variables. When components exceed the provided budget, the rows are shown in red. This illustrates a simple example of summations of the values and provides engineers with a useful tool to size systems. More complex relationships will require the use of parametrics.

Parametric Trade-off

An important factor in vehicle configuration will be the duration of the mission. The mission durations are specified as shown in Figure 10

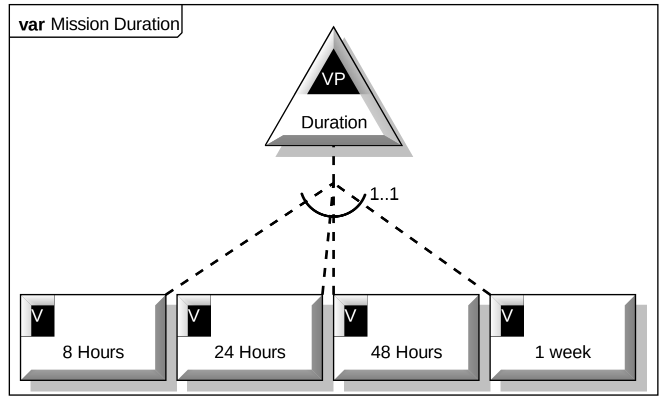

Figure 10 Mission Duration

The duration of the mission will determine the amount of equipment, food, fuel, etc. that will need to be taken. This may also require additional vehicles such as fuel trucks and other equipment. A diagram detailing high level mission parameters is shown in Figure 11.

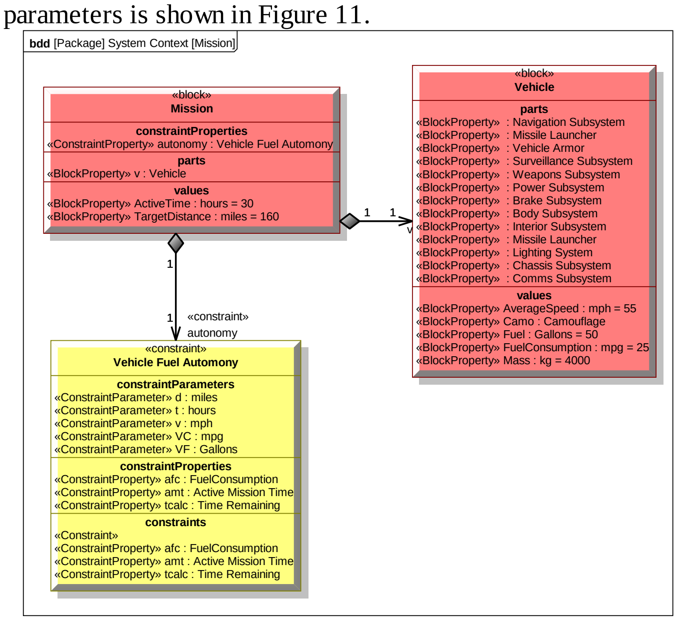

Figure 11 Mission Constraints

Figure 11 shows the mission made up of the vehicle and the Fuel Vehicle Autonomy constraint block. The mission has values such as the Active Time and target Distance. The Vehicle has Fuel, Fuel Consumption and others. Vehicle Fuel Economy has parameters such as miles, hours and MPH, properties such as Fuel Consumption and Time Remaining and a set of constraints. The Constraints are detailed in Figure 12.

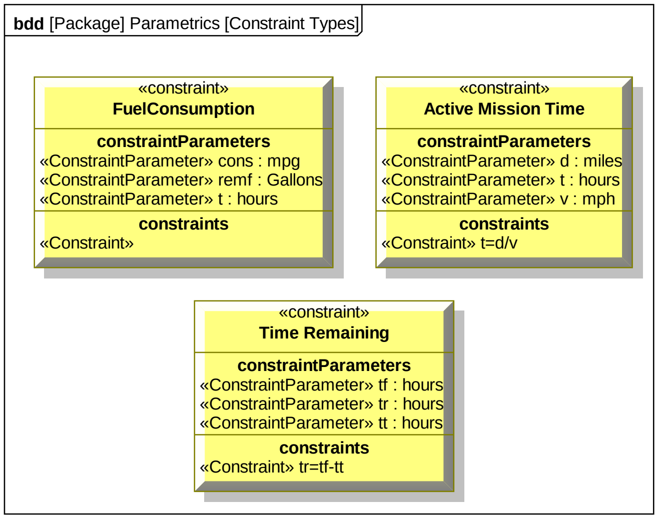

Figure 12 Fuel Parametrics Constraint Types

The constraint calculations, and parameters are listed as well as the units. Defining these elements provides the context for the calculations. They are further elaborated in Figure 13.

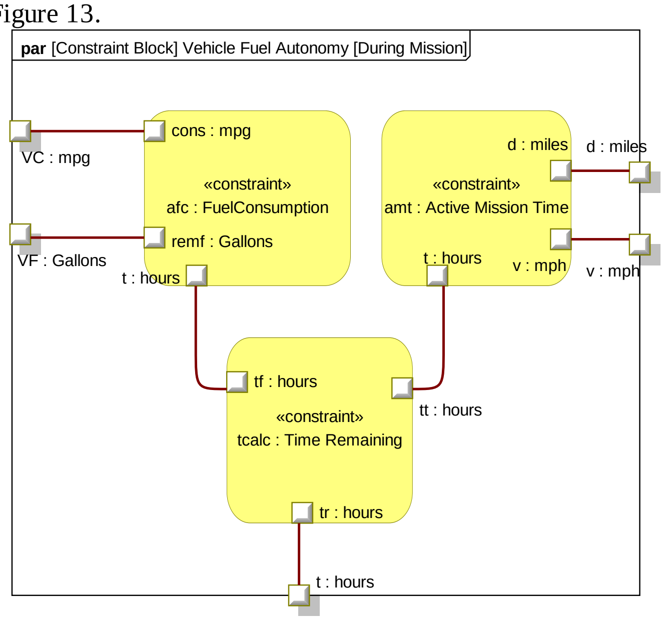

Figure 13 Fuel Autonomy [During Mission]

Figure 13 defines how the different calculations and parameters are all linked together to provide the necessary equations for trade-off analysis. Figure 14 shows how the specific mission and vehicle parameters are linked. The mission active time and target distance and vehicle fuel consumption, fuel capacity and average speed are used in the calculations. The overall fuel capacity can determined based on the mission time. Or, the mission time can be calculated based on the fuel capacity and other parameters.

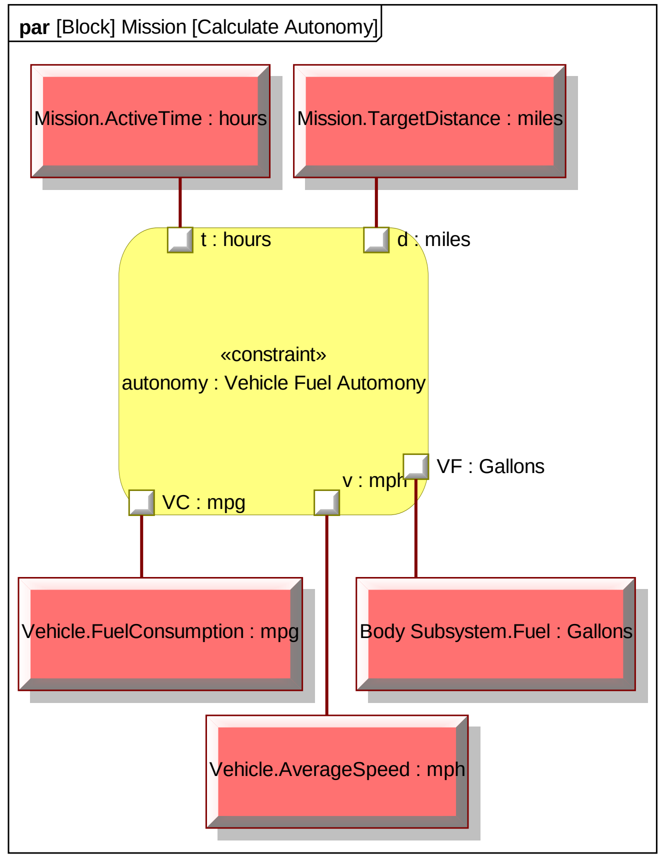

Figure 14 Calculate Autonomy

These simplified equations provide a means of calculating fuel usage throughout the mission to determine fuel needs. Power consumption and other more complex calculations can also be made. These calculations provide a means of sizing the fuel tanks and determining if the system configuration can meet the mission duration time frames. However, longer missions mean more equipment which will add to the overall weight and increase infrastructure requirements. An example of this is given in Figure 15 Mission time scales of 48 hours will require a food storage facility. Missions lasting a week will need to provide a sleeping facility. These additional subsystems will add to the overall vehicle weight. This may require additional load axles.

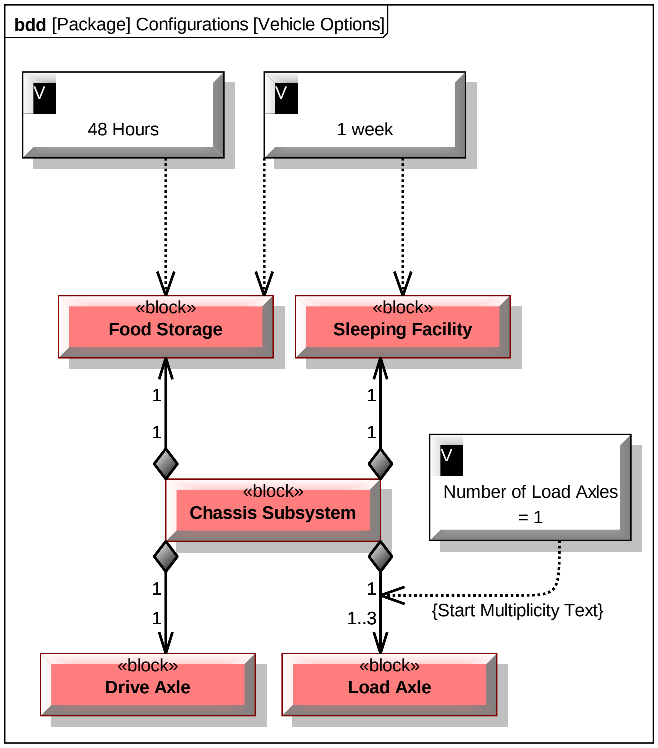

Figure 15 Vehicle Size Configurations

Calculations (not shown for simplicity) can be linked to the decisions as well as the different value properties. This provides a means of varying the number of system elements for a given configuration. Variant definitions can also require entry of values such as multiplicity and others when selecting variants. These would then be associated with the various choices and relationships, resulting in a decision hierarchy that provides a decision making framework for the vehicle configuration.

Conclusions

Having defined the decision criteria up front, the product development and configuration can be driven by these criteria. Requirements can also be linked to the variants as well as the system tests, activities, function elements, parameters and others. Independent survey results have shown that applying MB-PLE approaches can reduce total development costs by 62% and deliver 23% more products on time. [10, 11, 12] In today's budget constrained world these are numbers that demonstrate a return on investment that is worth investigating.

REFERENCES

[1] DoDAF DoD CIO, 2012, DoD Architecture Framework Version 2.02, DoD Deputy Chief Information Officer, Available online at http://dodcio.defense.gov/dodaf20/dodaf20_pes.aspx, accessed June, 2014.

[2] Friedenthal, S., Moore, A., Steiner, R. Practical Guide to SysML: The Systems Modeling Language Second Edition, Morgan Kaufman, Oct 31, 2011

[3] Object Management Group (OMG), June, 2012, OMG Systems Modeling Language (OMG SysML™), V1.3, OMG Document Number: formal/2012-06-01, http://www.omg.org/spec/SysML/1.3/PDF/, Accessed November, 2013

[4] Object Management Group (OMG), 2007a. Unified Modeling Language: Superstructure version 2.1.1 with change bars ptc/2007-02-03. [online] Available from: http://www.omg.org [Accessed September 2007].

[5] PALUNO, The Ruhr Institute of Software Technology Software Product Line Engineering (Pohl et al - Springer 2005)

[6] ISO 15288:2008 Systems Engineering standard covering processes & life cycle stages.

[7] ISO 26550:2013 for Software & Systems Engineering – Reference Model for Product Line Management & Engineering.

[8] OMG, 2005, Reusable Asset Specification (RAS), Version 2.2, http://www.omg.org/spec/RAS/2.2/PDF, formal/05-11-02

[9] INCOSE SE Vision 2020, September 2007, Available at http://www.incose.org/ProductsPubs/pdf/SEVision2020_20071003_v2_03.pdf, Accessed Nov 2013

[10] EMF 2013 Independent Survey Results from 667 Systems Engineering respondents, http://www.embeddedforecast.com/EMF_freewhitepapers43.php

[11] Linda Northrop, SEI SSPL 2008-2012), http://www.sei.cmu.edu/library/assets/spl-essentials.pdf

[12] Seven Years of Orthogonal Variability Model - Experiences and Insights" (A. Heuer et al. 2010)

[13] Intro to OVM at the SysML RTF" (V. Stricker, 2012)

.