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Application of Model-based Systems Engineering Methods to Development of Combat System Architectures

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Application of Model-based Systems Engineering Methods to Development of Combat System Architectures

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Abstract

Navy acquisition activities frequently produce combat system architectures based on existing systems rather than on stakeholder requirements. This approach limits software component reuse, which, in turn, limits potential application to other platforms. The objective of this Capstone project was to develop a methodology for creating complex combat system architectures that emphasize the use of Software Product Lines (SPLs), requirements traceability, integrated supportability and Modeling and Simulation (M&S) early and throughout the approach. To address this objective, an integrated methodology that utilizes Model-based Systems Engineering (MBSE) to create open, supportable combat system architectures was developed. The methodology was evaluated by applying it to a naval surface combatant Anti-Air Warfare (AAW) mission area. Application of the methodology led to the following major findings: (1) Proven systems engineering practices, languages and tools can be integrated with the MBSE approach for developing complex architectures; (2) Creation of domain-centered SPLs facilitates planned reuse and allows for assessment to candidate architectures; (3) Requirements traceability can be achieved by using a combination of modeling languages and tools; (4) M&S application can extend beyond operational scenarios to address lifecycle cost, and (5) Engineers and logisticians can effectively use MBSE to integrate supportability into design. Overall, this project demonstrated the benefits of an MBSE approach tailored to developing affordable and supportable combat system architectures that meet mission requirements.

Overview

This paper is a description of the Master of Science in Systems Engineering Capstone project completed by the students of Cohort Six from Naval Surface Weapons Center, Port Hueneme, CA. They were assigned this problem because Navy acquisition activities frequently produce combat system architectures based on existing systems rather than on stakeholder requirements. This approach limits software component reuse, which, in turn, limits potential application to other platforms. The development of systems tends to be by platform rather than by application or warfare area. A second system development issue is that *Department of Defense Instruction* (*DoDI*) *5000.02* (2008) prescribes the early integration of supportability requirements; however, current methods or processes do not do so. Methodologies currently in use—such as the Acquisition, Technology, and Logistics framework—may identify supportability as a requirement but tend not to maintain it as a priority throughout the development process.

In response to these issues, an integrated methodology that utilizes MBSE and the Agile process was defined to create open and supportable system architectures. This methodology incorporates a common modeling language, utilizes domain analysis to support Software Product Line (SPL) reuse, maintains traceability of requirements and architecture functionality, and integrates supportability, sustainment and lifecycle cost considerations. Also described in this project is a system engineering process that outlines requirements generation analysis, functional analysis and allocation, architecture definition, and Verification and Validation (V&V).

The methodology was evaluated by applying it to an Anti-Air Warfare (AAW) mission thread—in particular, Anti-Ship Missile Defense (ASMD). The AAW implementation included the development of a systems architecture and design artifacts, including Department of Defense Architecture Framework (DoDAF) views. The project demonstrated the benefits of an MBSE approach tailored to developing architectures that support Open Architecture (OA), SPL, and integrating supportability early in the system development process. Technical conclusions resulting from the research, development and application of the methodology are summarized in the following paragraphs.

Problem Statement and Capstone Objective

Recognizing that current DoD processes for developing combat system architectures are heavily influenced by legacy processes and systems—which inhibit the incorporation of supportability requirements up-front in design—project leaders assigned the students to meet the DoD objective of acquiring and fielding interoperable, supportable system architectures that utilized the Open Architecture (OA) paradigm. They were further tasked to address the use of Software Product Lines (SPLs) and capture the results in a form that was compliant with the DoD Architecture Framework (DoDAF). They were specifically told to develop a MBSE approach. In addition, they were to integrate supportability issues, requirements traceability and identify a structure which supports combat system software reuse.

Project Organization

Figure 1 shows the various organizational structures the students adopted as they progressed through the project. At first there was a reluctance to change, but eventually they learned that they had to adapt the organization to the task. Once that lesson was learned, the students became proficient in developing their work products.

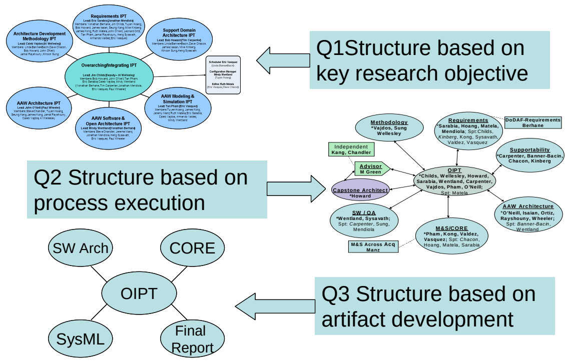

Figure 1. IPT Structure Evolving with Capstone Project Need

Two other lessons learned were that small teams were more efficient and that the project needs a chief architect.

Methodology Overview

The result of the literature searches into each element of the problem set is summarized in Figure 2.

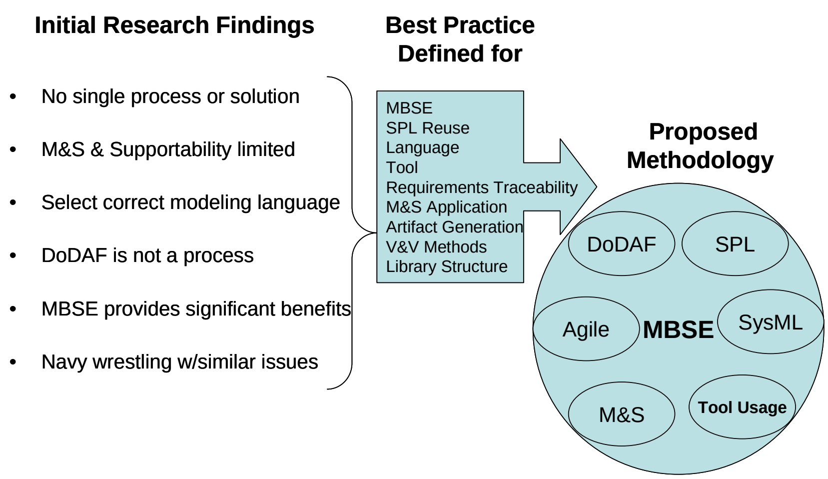

Figure 2. Overview of the Model Development

The initial research findings are significant in that the students came to understand that development of complex systems requires a through understanding of processes and tools available. Figure 3 illustrates how the students integrated the literature with practice.

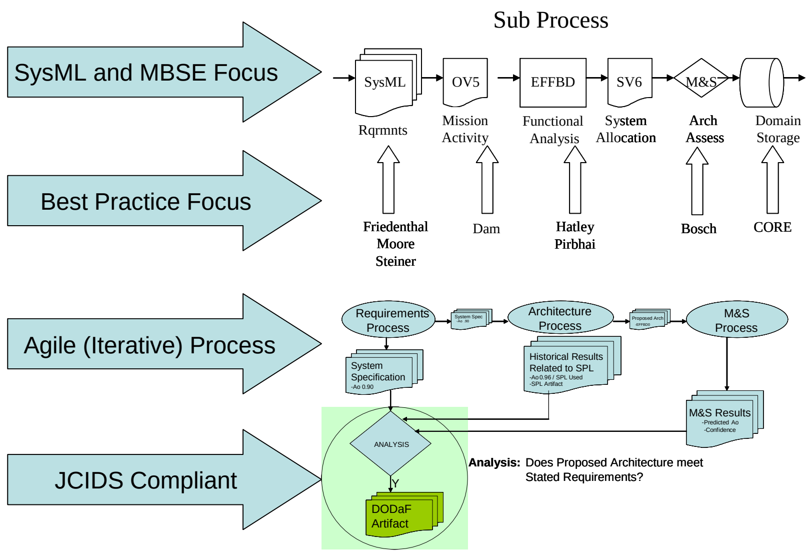

Figure 3. The Big Picture

Two of the takeaways from Figure 3 are these: 1) to deal with complex problems, one requires multiple frames of reference, and 2) integration of methods is needed to provide a more complete description of the potential solution. The following paragraphs provide more detail about the approach the students developed.

Methodology Top-tier Process

Figure 4 is the representation of how the students viewed the process of going from a specification to architecture.

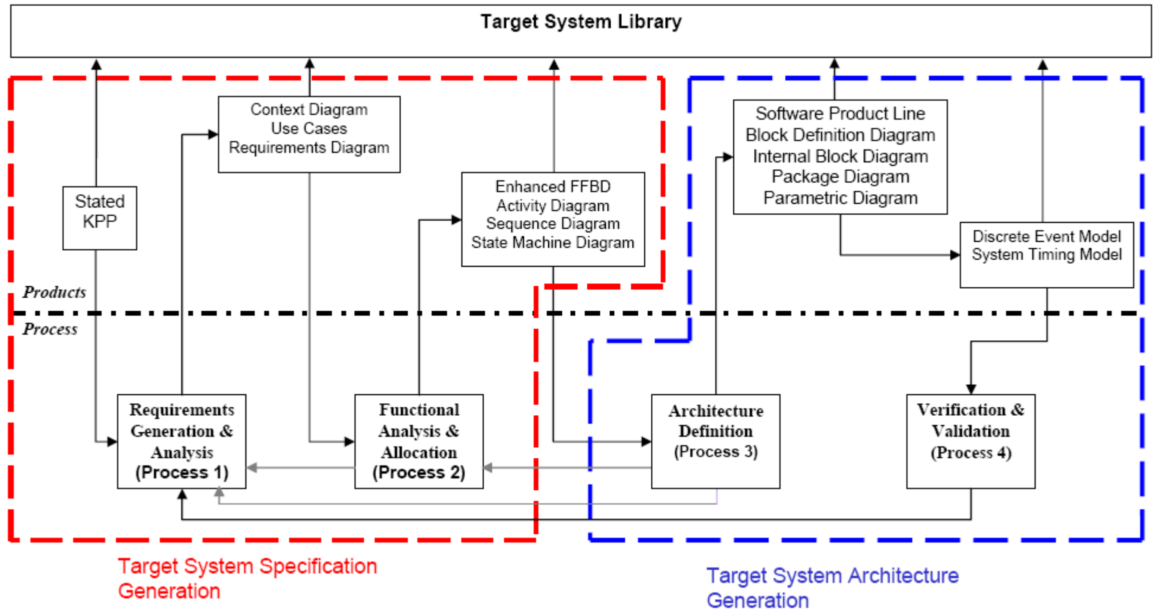

Figure 4. The Overall Methodology

They developed four main processes as shown in the figure above: (1) requirements generation and analysis, (2) functional analysis and allocation, (3) architecture definition, and (4) verification and validation. They verified these processes by developing an AAW Mission Architecture. The following paragraphs describe the four sub-processes.

(1) Requirements Generation and Analysis Process

Figure 5 provides the detail of the requirements generation and analysis step and how it interfaces with the other three steps in the methodology. Figure 6 shows the outcome of the requirements step.

Requirements lessons learned can be summed up as follows:

- It was necessary to expand the use of modeling because of the insights it provided in requirements decomposition and allocation. M&S can result in improved decomposition and allocation.
- It was important to understand the relationship between requirements artifacts for traceability at the tier level and across artifact boundaries.
- It was essential to keep the requirements tool set database current for both traceability and verification of allocation.
- Process execution improved over time; i.e., the teams became more effective with experience.
- The process resulted in valid artifacts that support Capstone objectives.
- The tools, skill sets, and processes are not in place to lead requirements development on large, complex systems.

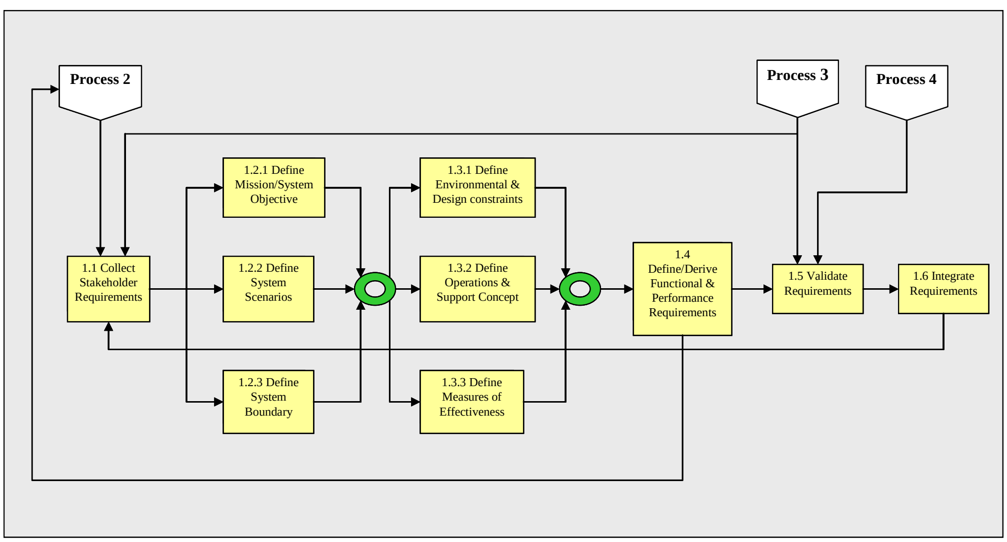

Figure 5. The Requirements Generation Process

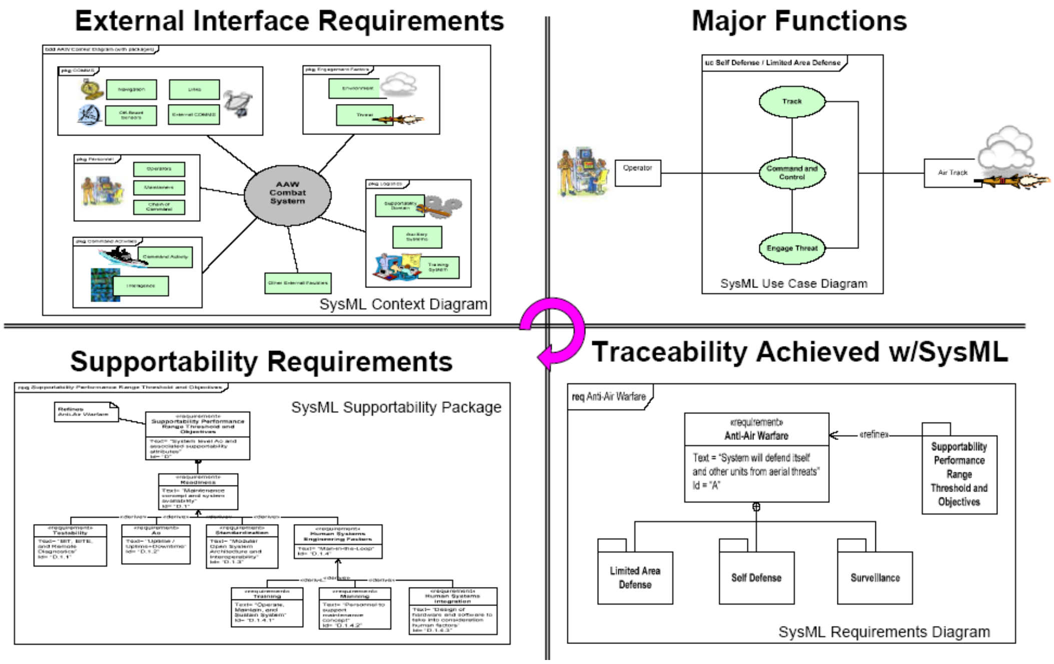

Figure 6. Requirements Results/Products

(2) Functional Analysis and Allocation Process

The approach to functional analysis was straightforward and is shown in Figure 7. Some of the key lessons learned were to plan tool usage. The process is iterative, and the data is developed in a drill-down manner. A second point was that to ensure that the result is correct, a subject-matter expert (SME) is important and should be readily available; otherwise, there is a tendency for engineers to map based on experience. The level of input is only as good as the SME's knowledge. It should be noted that technical, language, method, and tool SMEs are different and that a blend of talent is required.

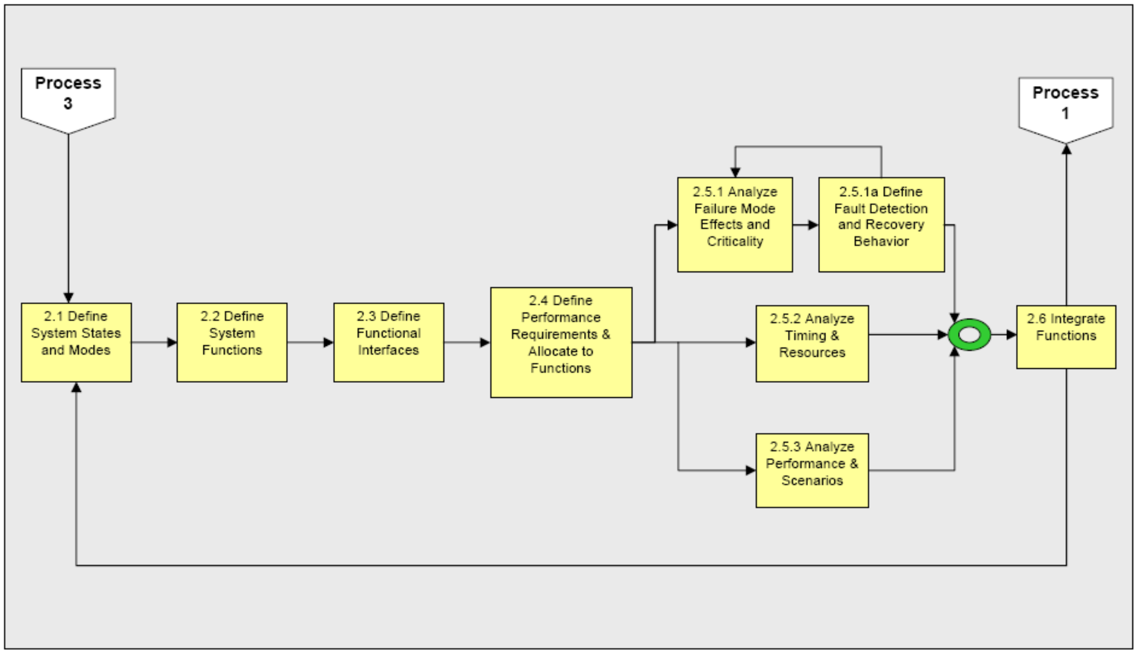

Figure 7. Functional Analysis Process Diagram

Figure 8 shows some of the key artifacts developed during this part of the process. The artifacts provided powerful depictions for communicating and for analysis in design and development.

In the execution of the process, the Hatley-Pirbhai method was integrated with the SysML language to provide a sound SE approach within the MBSE format. The outcome of this approach is a requirements model, as shown on the left side of Figure 9. The architecture process diagram illustrates how the students built the right side of the model.

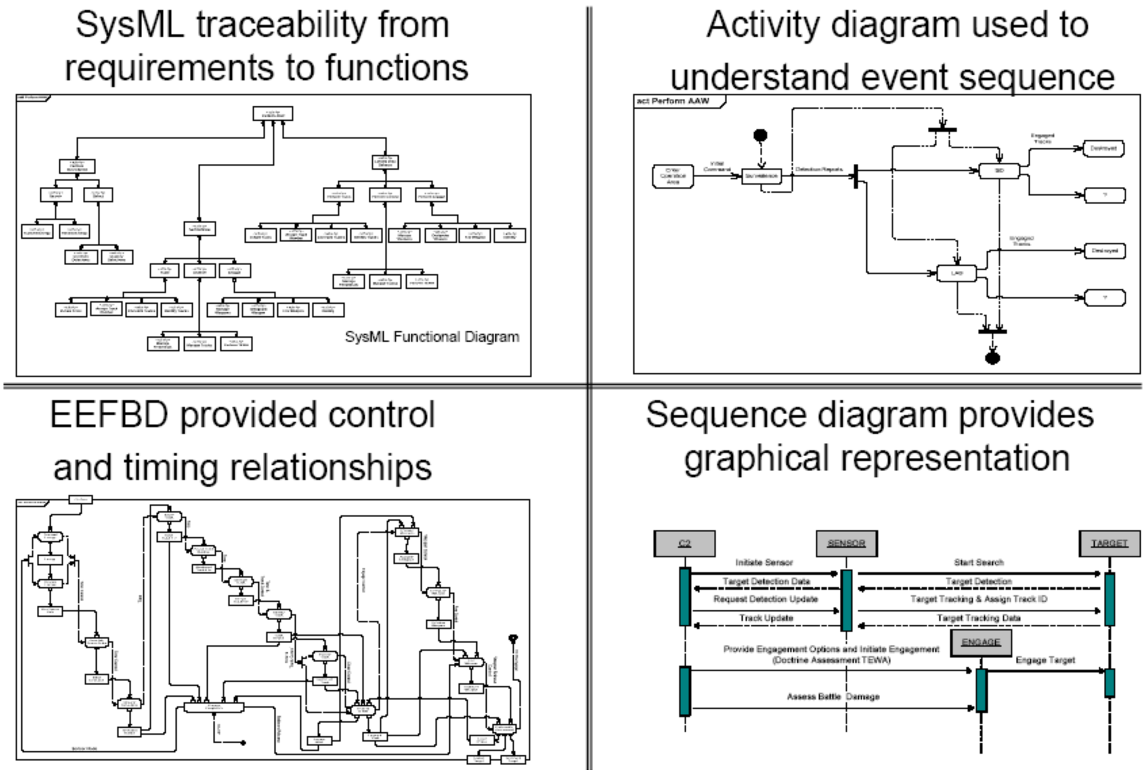

Figure 8. Functional Analysis Results/Products

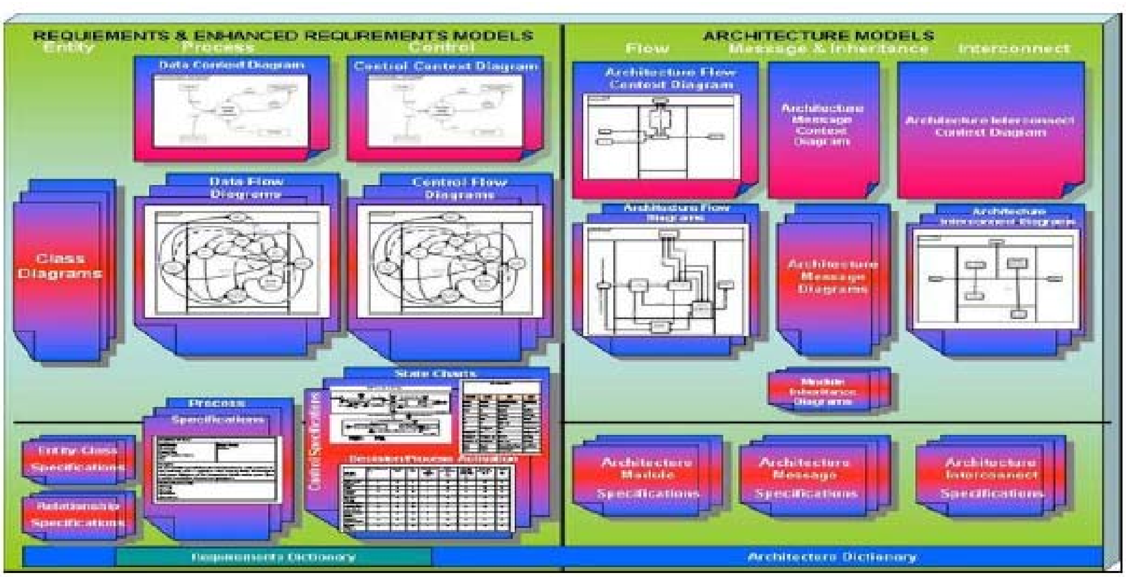

Figure 9. The Hatley-Pirbhai Models

(3) Architecture Definition Process

The development of the architecture followed the process shown in Figure 10. In developing the architecture from the previous step, the students encountered some interesting issues. First, there was a lack of core knowledge in the architecture development process. Use of the Hatley-Pirbhai paradigm provided an approach that overcame the inexperience issue. Figure 11 is the Hatley-Pirbhai architecture template. This template is reusable at every level of analysis and allows for a more formal approach than natural language descriptions.

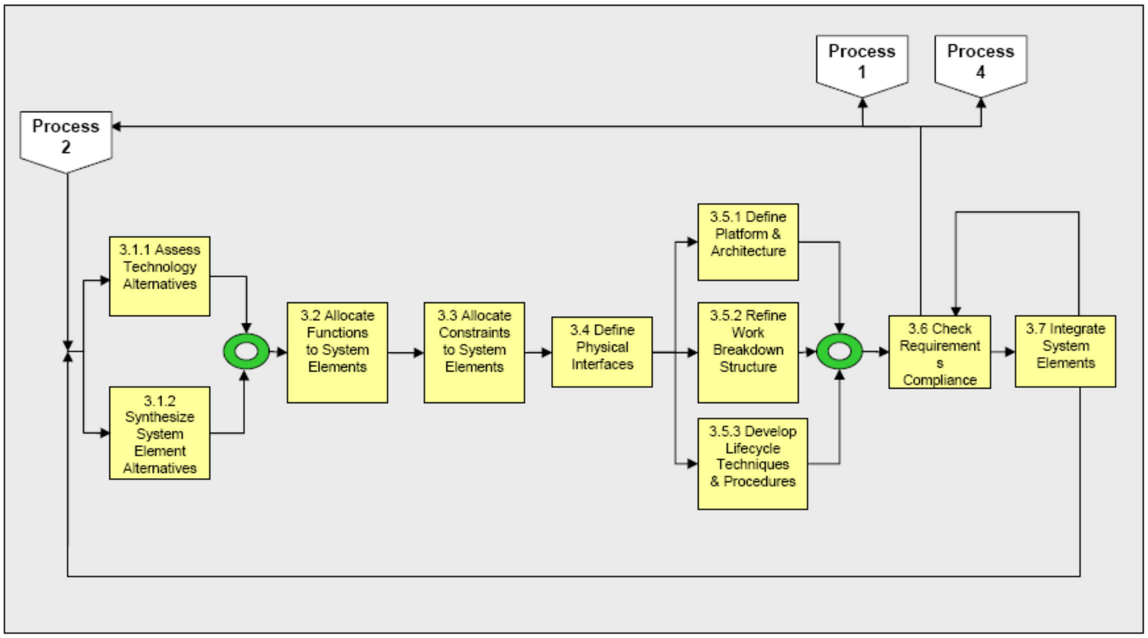

Figure 10. Architecture Process Diagram

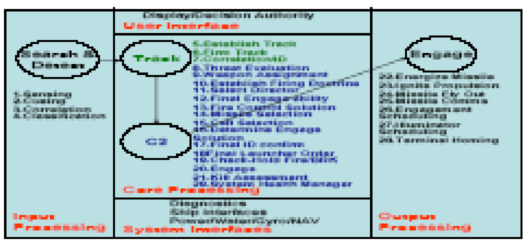

Figure 11. Hatley-Pirbhai Architecture Template

There was also an issue with software architecture quality attributes not being fully defined or measurable. The student solution was the use of an objective hierarchy to assess architecture, as shown in Figure 12. One of the subtle realizations by the students was the applicability of Six Sigma techniques to all the steps discussed so far.

The students initially had a problem with a lack of common task and function descriptions. This was caused by different teams working on different parts of the problem using different tools. This issue was resolved as the students reorganized and reduced the size of the team working on this area.

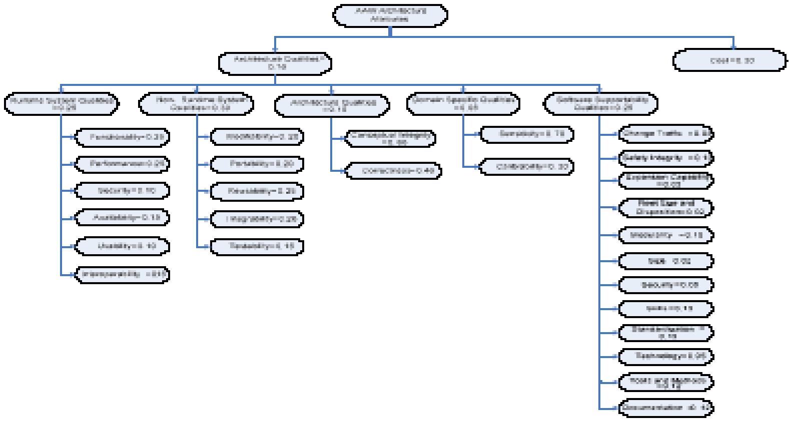

Figure 12. SW Architecture Objective Hierarchy

This reorganization helped with developing the software architecture shown on the left side of Figure 13. Figure 13 shows the relationship of the software architecture to the production plan (much simplified in this diagram) to the product line library on the right.

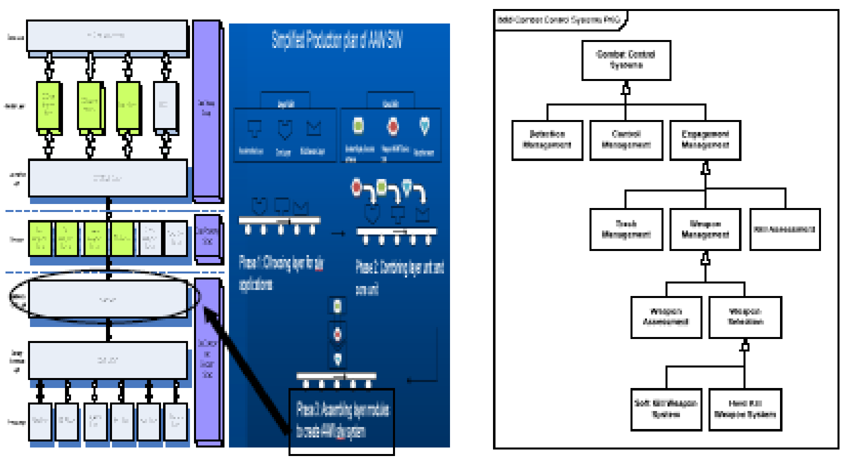

Figure 13. Project Software Architecture and SPL Library Framework

(4) Verification and Validation Process

As shown in Figure 14, modeling and simulation was used to identify both feasibility and configuration performance differences, as well as to verify requirements. The parallel analysis efforts for functional analysis and architecture development required adaptable models that could be updated as Systems Engineering artifacts were created. The students initially had problems with trying to put too much detail into the model rather than focusing on process execution. As they gained experience, they were able to use a block-oriented simulation language to develop model variations very quickly.

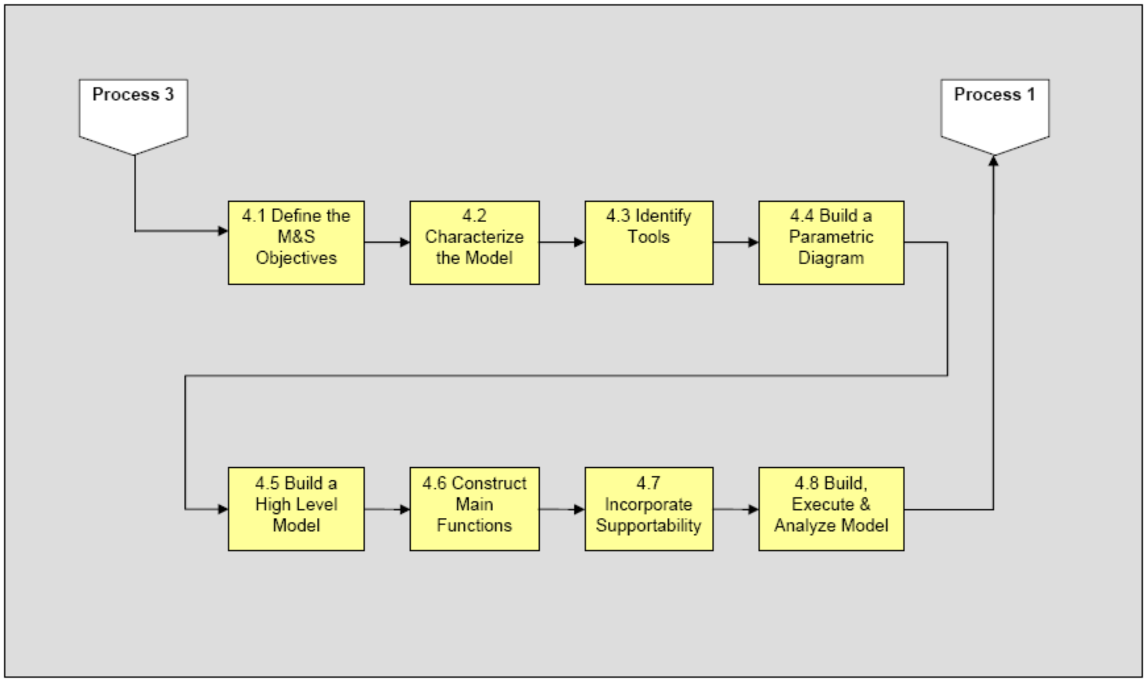

Figure 14. M&S Process Diagram

Overall, M&S provided valuable insight into architecture design, requirements decomposition, and related performance issues.

Capstone Conclusions and Recommendations

The students made the following recommendations. First, provide logisticians with the background to participate early in the acquisition cycle. In this study, logisticians demonstrated the required skills to work in systems concept and development. Second, establish domain-specific components and quality attributes. Identify a QA weighting system to balance sustainment and performance by domain. Third, develop SPL library criteria and characteristics. Define data tags required to assess SPL reusability. Fourth, continue the research effort to a V&V methodology. Execution of the methodology to develop S/W, H/W and Interface Components will result in additional findings/lessons learned. Finally, leverage the methodology to estimate lifecycle cost and RAM through M&S, and use artifacts to support early LCCE and RAM KPP reporting requirements.

Overall Project Summary

Proven systems engineering practices, languages and tools can be integrated with the MBSE approach for developing complex architectures. Through decomposition of the objectives and associated research, the students were able to identify many solutions and methodologies available to support a top-down or bottom-up approach. Based on tenets from multiple authors, the student teams developed a new end-to-end methodology for system design—to include key aspects in requirements generation, architecture development, and modeling and simulation.

Requirements traceability can be achieved by using a combination of modeling languages and tools. Traceability is critical on large, complex systems due to the sheer volume of technical data and the likelihood of human error when trying to conduct V&V manually using engineering artifacts. Students achieved requirements generation and traceability using the Systems Modeling Language (SysML) as the modeling language and CORE as the architecture tool. They reduced manual V&V errors, given that SysML contains methods based on the allocation relationship depicted in the artifacts for verifying traceability. They used sample test criteria and events to successfully verify that CORE could be used to assess demonstration of requirements.

M&S can provide significant value in conducting tradeoffs during design. However, the majority of M&S is focused on verifying operational parameters within scenarios vice optimizing system design. Students applied M&S using a top-down approach to verify system operational behavior and to validate initial operational requirements. They used the software tool Extend to perform the simulation of a raid scenario. Through multiple variations of models and simulations, it was found that there could be anomalies or elements that need adjustment in the architecture. The unexpected results from the raw data led to more extensive research of the initial inputs, which led to additional simulation runs. Defining objectives, processes and model development were all key milestones in building the Extend model.

Engineers and logisticians can effectively use MBSE to integrate supportability into system design. The Navy advocates the integration of supportability early in the concept development and design phases, but very little training or guidance is provided on how to effectively do this. Many logisticians are not equipped with the knowledge or experience to adequately support initial system concept and architecture development. Similarly, many design engineers lack the training and experience of considering supportability during concept exploration, design and development. On this project, engineers and logisticians collaborated to meet the expressed objective of integrating supportability into design as depicted in the resulting artifacts. Supportability was considered during requirements generation, functional analysis and architecture composition. The integration of supportability early in design provided the maintenance concept and planning phases with a solid foundation for conducting tradeoff decisions between operational enhancements and lifecycle sustainment considerations.

List of References

MSSE/MSSEM Cohort 6. (2009, March). Application of model based systems engineering methods to development of combat system architectures (NPS-SE-09-002). Monterey, CA: Naval Postgraduate School.

USD (AT&L). (2008, December 8). *Operation of the defense acquisition system* (DoD Instruction 5000.02). Washington, DC: Author.

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