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THESIS

THE INTEGRATION OF RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) INTO MODEL-BASED SYSTEMS ENGINEERING (MBSE)

by

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Model-Based Systems Engineering (MBSE) methods have developed a strong foothold in the design space in industry. These methods have proven fruitful when the right method is applied to the right problem. Reliability, Availability, and Maintainability (RAM) and associated techniques are equally important. Currently, there is a gap in applying a methodology to integrate the two in the design process, particularly when the design is complex. This work attempts to provide a methodology that results in the successful integration of RAM and MBSE that can be used during the early phases of design. The methodology was developed after an extensive literature review, followed by validation of the methodology through a use case where each step of the method is applied to a turbine fuel system. The application of the seven-step methodology demonstrate its validity and acts as a simple blueprint for the integration of RAM and MBSE techniques to effectively inform a design effort.

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THE INTEGRATION OF RELIABILITY, AVAILABILITY, AND MAINTAINABILITY (RAM) INTO MODEL-BASED SYSTEMS ENGINEERING (MBSE)

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ABSTRACT

Model-Based Systems Engineering (MBSE) methods have developed a strong foothold in the design space in industry. These methods have proven fruitful when the right method is applied to the right problem. Reliability, Availability, and Maintainability (RAM) and associated techniques are equally important. Currently, there is a gap in applying a methodology to integrate the two in the design process, particularly when the design is complex. This work attempts to provide a methodology that results in the successful integration of RAM and MBSE that can be used during the early phases of design. The methodology was developed after an extensive literature review, followed by validation of the methodology through a use case where each step of the method is applied to a turbine fuel system. The application of the seven-step methodology demonstrate its validity and acts as a simple blueprint for the integration of RAM and MBSE techniques to effectively inform a design effort.

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List of Acronyms and Abbreviations

BDD Block Definition Diagram

DAF Data Architecture Framework

DOD Department of Defense

DODAF Department of Defense Architectural Framework

FAS Functional Architectures for Systems

FMECA Failure Mode Effects and Criticality Analyses

IDEF Integrated Definition Methods

MBSE Model-Based Systems Engineering

NPS Naval Postgraduate School

OPM Object Process Methodology

RAM Reliability, Availability, and Maintainability

SysML Systems Modeling Language

UAF Unified Architecture Framework

UML Unified Modeling Language

USN United States Navy

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Executive Summary

Systems are becoming increasingly complex and so too must the design processes and methodologies that support them if they are to be successfully executed. Traditional paper-based processes of conducting systems design are antiquated and no longer able to take full advantage of the latest advantages, features, and functions of modern design processes and methodologies. As a result, model-based systems engineering (MBSE) methods are being increasingly relied on to develop and execute models that underlie many systems design processes to better facilitate complex system design.

Several known issues have arisen when attempts to integrate reliability, availability, maintainability (RAM) and MBSE have been made in the conceptual design phase of a system. The first issue is that RAM is not fully integrated as a focal point of the design process, being relegated to an activity to get a "check in the box" and continue with the design process. The second issue arises around the timing when RAM is conducted—namely, the design team disagrees internally as to when it should be conducted. The inability to identify the point in time when RAM analysis should be conducted adversely impacts design, often leading to disastrous results. Reliability calculations may be conducted to provide a needed numerical value, but the calculations are not performed early in the design process. The effort and resources needed to realistically attain the needed value may cause significant delays or overruns in cost, with the worst-case scenario causing the dissolution of a project and its team. The potential undesired realization of this scenario creates the gap in RAM and MBSE integration that this work seeks to address.

To navigate design efforts and bridge the gap between RAM and MBSE integration efforts, a seven-step methodology is proposed to facilitate the integration of RAM and MBSE processes:

Step 1: Define for the design effort the modeling language, structure, modeling process, and presentation framework.
Step 2: Select an MBSE tool that can completely represent the system.
Step 3: State system relationships/requirements.
Step 4: Construct block definition diagrams (BDDs) and consider additional diagrams and

tool(s) as needed.
Step 5: Define data requirements and gather data.
Step 6: Make parametric diagrams.
Step 7: Determine RAM values from parametric diagrams and compare to requirements.

This process is intended to provide a methodology to get from a design concept to a descriptive and logical system, and subsystem states. Proper tool selection through an analysis of modeling language, structure, modeling process, and presentation framework will make it easier for the engineer to create the BDD and parametric diagrams while also showing the appropriate relationships and requirements. As stated in Step 4, the designer can use additional, more robust tools as needed to provide more detailed models and simulation results for analysis. The analysis as to the feasibility of the methodology was conducted through the application of an illustrative example. This illustrative example references real world data with the methodology applied to show that the methodology presented is valid.

The results confirm that the methodology can be applied successfully to a real-world situation. A limitation was noticed that the methodology is best suited for designs where historical data is readily available. If historical data is not available, then assumptions must be made for certain values to determine results. If the diagrams in the early steps are made are correctly, however, the process of following the methodology becomes easier as the design effort progresses.

The methodology presented provides a basic blueprint for effectively combining RAM and MBSE. Following the steps in order provides the optimal opportunity for saving time and reducing potential for rework, lowering cost and scheduling overruns on the project. Beginning with Steps 1 and 2, the primary drivers in the MBSE realm are determined and selected based on the design needs. Stating the system relationships in Step 3 shows how the different parts of the system interact. Step 4 is informed by the relationships and the effective creation of BDDs and other diagrams as needed. The incorporation of other tools to provide additional data or information should not be ignored despite the possible increase in time required to use the newly implemented tool effectively. If initial MBSE tool selection is limited in certain aspects, the incorporation of other tools and time to gain proficiency, if not achieved already, should be accounted for to provide the best long-term chance for success.

Defining data requirements, gathering the primary and secondary data, and ensuring data quality provides the foundation for getting the desired results needed for analysis. Making and evaluating the parametric diagrams and comparing them to requirements incorporates MBSE and RAM techniques, culminating in usable information for the engineer to decide on the design process. The comparison is critical for checking the processes of the design effort to determine if a single step or multiple steps need to be readdressed to the desired degree.

There are multiple benefits from applying this methodology to a design effort. First and foremost, a clear way to navigate the integration of RAM and MBSE techniques is laid out. This results in savings of time and cost on the backend through getting RAM information earlier in the design process, thus informing changes to the design earlier in the process. Another benefit is the expansion of knowledge in this field of integration. The methods for joining RAM and MBSE techniques more effectively is incredibly valuable to the cost and schedule minimization. The topic sponsor will input the findings by checking their own process against the methodology developed. If there is an area where incorporating the methodology will improve their own processes, they will make the necessary changes to gain the maximum benefits.

The priority for future work should be to determine the changes necessary to better suit this methodology to new design efforts for which minimal or no data is available. This would provide two different methodologies, each with its own set of characteristics and uses. The application of this methodology to a new design would be the best way to determine its feasibility.

There are four further areas of interest for future work:

1: Determining a methodology for using multiple tools at once and seamlessly transitioning between those selected.
2: Determining the effectiveness of this method using a different tool or modeling language.
3: Determining the feasibility of this method when incorporating multiple system models across various languages and tools.
4: What changes should be made to make the method presented better suited for wider application and distribution.

These areas for future research would expand upon the current work done in a meaningful way. This methodology would be tested in various conditions not touched on in the current work, which would provide further refinement to the methodology presented.

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To my wife Alix, thank you for being patient with me over the last year. You took care of everything and then some, I couldn't be happier to have your support. To my parents, thank you for listening to me ramble about RAM and MBSE techniques.

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CHAPTER 1: Introduction

This introductory chapter provides the background and motivation for the conducted research. Systems are becoming increasingly complex and so too must the design processes and methodologies to be successfully executed. Old paper-based processes of doing system design are no longer capable of taking full advantage of modern design processes and methodologies. As a result, Model-Based System Engineering (MBSE) methods are being increasing relied on to develop and execute models that underlie many system design processes to better facilitate complex system design. The research conducted in MBSE has largely been successful in the execution of thorough design processes and robust analysis capabilities. Additionally, historical data can be effectively leveraged to aid with requirements development and conceptual designs.

An important step in assessing a system design occurs when executing a reliability, availability and maintainability (RAM) analysis. These analyses are usually assessed after the design of a system has largely been finalized, and even if the assessment shows that a change should be made, changes are not often implemented; usually the analysis is treated as a paper after-the-fact activity. A potential way to improve the situation is to better integrate RAM analysis into MBSE so that RAM is performed earlier in the system design process when RAM can influence the design. Currently, RAM analysis is not effectively influencing the design of a system.

There have been several issues that arise when attempts to integrate RAM and MBSE are made in the conceptual design phase of a system. The first issue is that RAM is not a focal point of the design process, being relegated to an activity to get a "check in the box" and continue with the design process. The second issue arises when it is conducted, because there is not a unanimous agreement from the design team as to when it should be conducted. The inability to identify when RAM analysis should be conducted often has disastrous results. Reliability calculations may be conducted to provide a needed numerical value but if it is not conducted early in the design process, the effort and resources needed to realistically attain the needed value may cause significant delays or overruns in cost, with the worst-case scenario causing the dissolution of a project and its team [1]. This scenario highlights the gap in RAM and MBSE integration.

This thesis intends to provide a solution to the following research question: how can RAM/MBSE integration be achieved during the early stages of the design phase? The solution presented in this thesis is in the form of a methodology developed simply enough to be followed with minimal steps, but also contain the necessary information to be effective in both the RAM and MBSE domains. The first step to providing a solution to this question is through conducting a literature review, located in Chapter 2. The literature review consists of an in-depth examination of RAM and MBSE methodologies, to include the historical and current state of RAM and MBSE domains, both individually and integrated. Major topics of this literature review include what integration has currently been done in RAM/MBSE domains, what processes or frameworks exist that have been, or show potential to, act as a blueprint for successful integration, and what pitfalls, if any, have been discussed to effectively integrate RAM/MBSE methods.

With the literature review conducted, work on the development of a methodology begins, located in Chapter 3. The literature review provides the background information and guidance to develop the methodology. The development of the methodology incorporates information from the literature review, namely what has been successful or problematic with RAM/MBSE integration efforts and what techniques can be effective if implemented in a particular way. The developed methodology is then applied in two examples. The first example is an Automobile Braking System, located in Chapter 3. The second and more comprehensive example is applied to a Steam Turbine Fuel System, located in Chapter 4. This example shows how the methodology developed in Chapter 3 can be applied to a real-world scenario. The last section of this chapter is dedicated to an extensive discussion of this methodology and the results. The final chapter, Chapter 5, details the conclusion learned from the application and reflection on the methodology. The conclusion section is followed by detailing avenues for future work.

The five chapters presented in this thesis provide the background necessary to understand the research question by means of the literature review. The developed methodology and application to various examples takes the theory of the methodology and demonstrates it can be used effectively in practice. The discussion of the methodology in Chapter 4 provides better detail as to what was effective and what needs improvement in future iterations. Lastly, Chapter 5 wraps up the thesis and provides areas for future work with this methodology. The overall approach taken in this thesis lends credibility to the work done with a comprehensive literature review, development of a methodology from that review, application to two examples and in-depth discussion culminates in an effective demonstration to the validity of the approach taken for the thesis.

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CHAPTER 2:
Literature Review of RAM/MBSE Integration

This chapter presents the Literature Review conducted in the area of RAM/MBSE integration. The historical uses of how RAM/MBSE are used separately in design is explored, with a focus on how, why and in what context. The review concludes with an exploration of ways in which RAM/MBSE have, and can be, integrated in a design effort.

Literature Review

MBSE methods have been used for several decades, with the pioneering work of MBSE methods being published in 1993 [2]. Since then, several modeling languages, tools, and frameworks have been designed and implemented in various industries to facilitate design efforts. Modeling languages, such as Systems Modeling Language (SysML), can be used depending on level of detail needed for design or system boundary requirements [3]. Object Process Methodology (OPM) serves as a Modeling Language and Methodology for the creation of conceptual models for the creation of a system [4].

Frameworks such as Digital Thread and Department of Defense Architectural Framework (DODAF) are some of the MBSE frameworks in use today by the Department of Defense (DOD) [5], [6]. Digital Thread is "a data-driven architecture that links together information generated from across the product lifecycle" [7]. Digital Thread is used in model-based manufacturing, additive manufacturing, and with hierarchical object oriented models [8]–[10]. Digital Thread can also applied with Digital Twin, as the United States Air Force is currently utilizing [11]. DODAF over the past few decades has also been expanded to allow for additional modeling and simulation and become the basis for some system of systems modeling and simulation efforts [12]–[14] With the advent of many MBSE methodologies, there are also frameworks with a set of criteria to evaluate which methodology is most practical based on anticipated uses [15]. The methods and frameworks listed have had taken into consideration, though not a focal point, of the effect that RAM has on system design.

There are several reliability prediction approaches in use today. Some of these are physics of failure prediction, historical failure data prediction, hybrid physics and data approach, and functional failure mitigation modeling [16]–[18]. Failure research in the stated areas consist of stored system of systems, systems with spurious emissions, off the shelf software components, power electronics, turbine blades, and oil pipelines [19]–[25]. Maintainability prediction methods using hybrid neural network, fuzzy logic, extreme learning machines and mixture frailty models have also been used to predict the maintainability of evolving software systems, object oriented systems, and mechanical components [26]–[30].

Reliability, availability and maintainability are important attributes that affect system design, life-cycle costs, and system utility. The origins of reliability engineering can be followed back to World War II, with an emphasis on electronic and mechanical components [31]. Since then, a significant amount of effort has been put into improving the body of work. The use of failure mode effects and criticality analyses (FMECA) has become the primary quantitative method for determining RAM characteristics [32]. Quantitative analyses to assess system reliability and availability have also been used, based on reliability block diagrams, fault trees and Markov models, used independently or combined to perform various analyses [33]–[35]. Works such as these laid the groundwork for the development of a joint standard adopted by the DOD defining four processes to be used throughout the development life-cycle [36].

Integrating other technologies and concepts with MBSE is a concept that has been around for some time. Technologies such as Digital Twin, originally introduced in 2002, is used to provide an accurate, digital representation of a physical system [37]. Recent work has demonstrated the effectiveness of leveraging Digital Twin technology in MBSE, specifically by making it a part of MBSE methodology and experimentation efforts [38]. Digital Twin has also been used prominently in industry, both in concept development and through simulations [39], [40]. Practically, a Digital Twin, used in conjunction with MBSE efforts, can provide an effective integrated modeling environment of the physical system. Digital Twin technology sees the most benefit in design efforts through predictive maintenance modeling and analytics to inform decisions made about the physical system in question [41].

Most of the relevant work utilizing RAM/MBSE integration provides very specific information using one aspect of RAM or MBSE. This includes quantitative reliability [42]and availability studies using SysML [43], Fault Trees through SysML Diagrams [44], MBSE-assisted FMEA approach [45], model-based architecting for RAM software in automotive applications [46], MBSE approach to develop reliability model of NASA Sounding Rocket Program [47] and high-level modeling in MBSE environment [48]. Banner-Bacin et al. applied an MBSE method for Combat System Architectures that may be used to determine RAM values of a system [49]. The work described can be helpful but only under certain conditions, such as needing to conduct FMECA using SysML as the modeling language. Vaneman details five important considerations for achieving maximum MBSE effectiveness. The considerations, or pillars, are the Modeling Language, Structure, Modeling Process, Presentation Framework and MBSE Tool. Vaneman proposes these pillars within two processes that use MBSE diagrams and its use in RAM applications [50].

An article published in the 26th Annual INCOSE Symposium details a framework that provides a way to integrate reliability and systems engineering. This framework is broken down into three phases, detailing requirements specification, design and development, and detailed design of the system [51]. This work goes on to reinforce that reliability practices adopted at the earliest stages of design have the highest positive impacts.

The results of this research intends to culminate in a methodology that fills a gap in RAM and MBSE integration. Namely, a methodology that can be easily followed to effectively incorporate MBSE and RAM techniques early in the design effort.

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CHAPTER 3: RAM/MBSE Integration Methodology

This chapter introduces the proposed RAM/MBSE integration methodology. A figure showing the overall methodology and discussion of each step will be explained. At the end of each step will be an example as to how that step can be applied to an Automobile Brake System.

Methodology

To navigate design efforts, a seven-step methodology is proposed to facilitate the integration of RAM and MBSE processes. Figure 3.1 shows a visual of the methodology and its intended flow. It is intended to provide a high-level view of how the steps of the methodology are connected.

The diagram shows the flow path for each step in the methodology. The user will follow each step in order until the final step, Step 8, is reached. The comparison of requirements to actual values will be conducted to determine if values are acceptable for the design effort. If they are unacceptable, then the user will return to Step 3 and review the work done at that step and every step after. The intention of returning to Step 3 is to review the work and processes done and ensure there are no mistakes in areas that are most likely to impact the final results. Descriptions of each step are presented throughout this section. Once all steps have been completed, the user can continue to the next phase of design.

Associated with each step is an example showing a possible application of the methodology. In this case, a Reliability Engineer is attempting to design and evaluate RAM attributes of a Brake System for an automobile. To effectively design this system, the engineer will follow the steps of the methodology. The last paragraph in Step 1 to Step 7 sections will describe the steps taken by the Reliability Engineer.

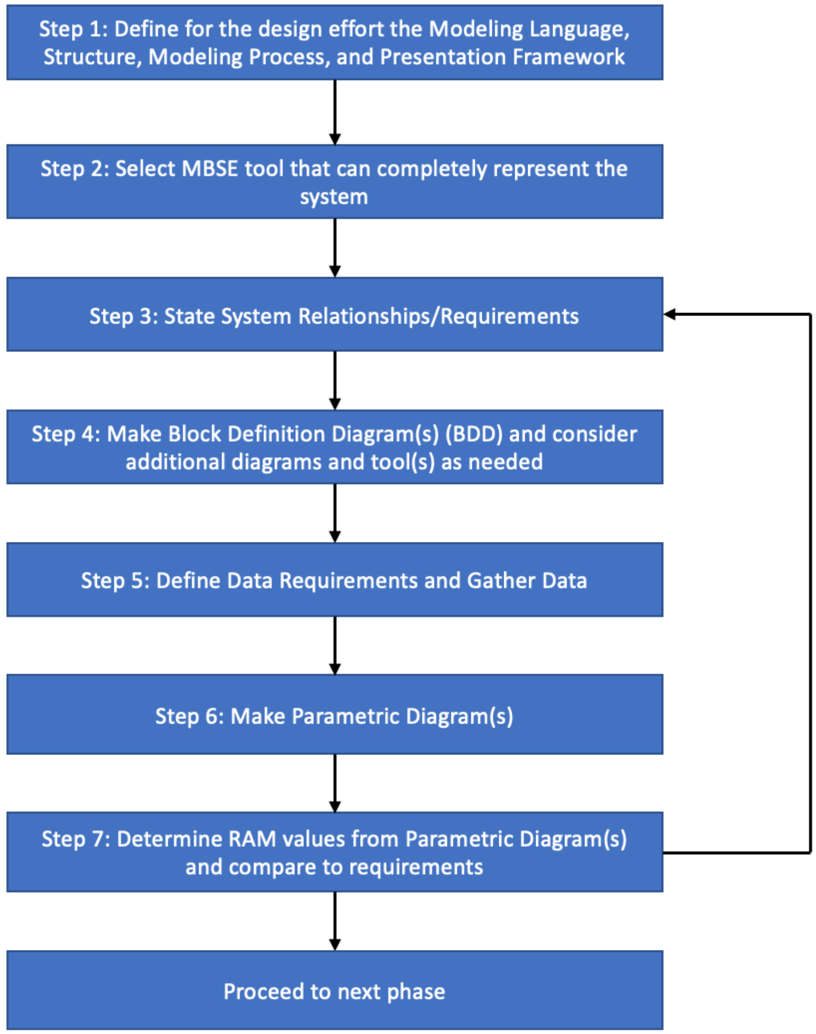

Figure 3.1. Seven-step methodology

Step 1: Define for the design effort the modeling language, structure, modeling process, and presentation framework

The first step for successful integration of RAM and MBSE is to first define the modeling language, structure, modeling process, and presentation framework. There are several modeling languages to choose from such as SysML, OPM or Universal Modeling Language (UML) [52]. The Structure defines the elements attributes and relationships within the model and their connections and interactions to establish model concordance [50]. The modeling process provides the analytical framework required to run and evaluate models.

There is a plethora of models that can be used so proper selection of the model early to inform the rest of the design effort is critical. Lastly, the presentation framework is intended to provide standard views, descriptions, and representations of the model to be presented to stakeholders in a logical manner.

This step should not be rushed, and adequate time should be spent to fully define what is needed for the design effort [50]. The implementation of an architectural framework, such as DODAF, can provide guidance on the four characteristics to be selected. This is done through explicitly stating how and what should be used but also allowing room for change as needed to accomplish the goal of the design effort. An example in practice would be to definitively select or narrow down the viable options based on the intended design. An awareness of the differences between two options in the same category, such as the modeling language SysML, which provides more advantages in terms of system and system-of system specification, than UML. Understanding the trade-offs of these choices is paramount to the effective selection and implementation of the next step.

Automobile Braking System Example: Based on previous use and subsequent familiarity, the Engineer will choose SysML as the modeling language, the structure used will be able to demonstrate the elements and relationships of an automobile braking system clearly and effectively. The Engineer has determined the Modeling Process will have an emphasis in the domain of RAM analysis through Monte Carlo simulations. The presentation framework will provide the standard view for showing the model and its results. This can be based on what the Engineer is used to using, or how the stakeholders want the information presented.

Step 2: Select MBSE tool that can completely represent the system

The selection of the MBSE tool comes after Step 1 because the MBSE tool is how the user interacts with the MBSE environment. There are several MBSE tools available with different capabilities and limitations. Because not every MBSE tool has the same capability and feature set, proper selection based on design considerations is crucial to the success or failure of the design effort. Table I below shows examples of some options shown in Step 1 and 2 as reference for what falls into each category. There are some instances where the tool used is mandated rather than selected. An example is tool selection for military projects generally use Cameo as their designated MBSE tool. It is important to understand that while mandating an MBSE eases the burden of needing to select a tool, the limitations must also be considered to adequately determine if success can be achieved.

There may be times when the MBSE tool chosen does not possess certain modeling or simulation capabilities or a better option may be available for this portion of the design effort. If more detailed modeling and simulation techniques are needed, other tools such as ModelCenter, which can provide an analysis from multiple perspectives due to the various options provided, can be used to provide the robust capabilities that may be required [53]. The selection of an additional tool may not happen until later in the design process. If that is the case, the additional tool should provide a capability that the current selection doesn't. Capabilities such as different diagrams or an add-in that makes calculating the values of certain requirements would be good tools to consider adding to the design effort. The table below shows some examples of modeling languages, processes, frameworks and MBSE tools that are available for use. MBSE tools generally rely on one modeling language but can be used with different processes and frameworks depending on design needs. It is up to the user to pick the best option or options and make the determination that will best suit the goals of the effort.

Table 3.1. Examples of modeling languages, processes, frameworks and MBSE tools

Languages	**Processes**	**Frameworks**	**Tools**
IDEF	AGILE	DODAF	Cameo Systems Modeler, CORE
OPM	Vee	FAS	Rational Rhapsody, Innoslate, OPM
SysML	Waterfall	DAF	SParx Enterprise Architect
UML	Spiral	UAF	Visual Paradigm

Automobile Braking System Example: With an understanding of how the necessary aspects of the design effort will be implemented, the Engineer has several tool options to choose from. Cameo Enterprise Architecture (CEA), CORE, and Innoslate are the tools that the Engineer can select from. Each of the MBSE tool options provide similar capabilities, however, after careful consideration of tool capabilities and user-familiarity the Reliability

Engineer chooses the CEA MBSE tool.

Step 3: State system relationships/requirements

The system requirements of the design effort are determined during the initial phase of the design process. Some activities that are conducted to effectively determine and document requirements are elicitation, analysis, validation, negotiation, documentation, and management [54]. These activities are conducted with the consideration of certain factors, such as stakeholder needs and system application. Requirements that an be determined through the previously listed activities are usability, functional, performance, operational and interface requirements. The functional, performance, and usability requirements are ideal for this method as these requirements deal with defining system functions and associated measures of performance such as reliability and availability.

System relationships consider how each system or subsystem for the design effort are connected. Understanding the interactions between the systems provide clarity as to how certain interactions can provide what is needed to meet the system requirements. The system relationships are considered in Step 1, but become more detailed in this step. There is a high likelihood that every relationship for the system may not be stated in this step based on available information and understanding of the system. As the design effort progresses to the following steps, the user may need to return to this step and update the relationships as appropriate to ensure continuity for the rest of the methodology.

Automobile Braking System Example: With the MBSE Tool selected, the Engineer can now interact within the MBSE environment. The system relationships and requirements will be stated for the brake system in the tool design space. These requirements were identified prior to tool selection and any new or altered requirements are updated as needed.

Step 4: Make block definition diagram(s) (BDD) and additional diagrams as needed

The purpose of a Block Definition Diagram (BDD) is to show “system components, their contents (properties, behaviors, constraints), interfaces, and relationships” with the intention of providing the building blocks to create a robust model of the system [55]. BDDs are scalable and can provide a high-level overview or specifics of a subsystem. In some cases, however, additional diagrams may be needed. Diagrams such as fault tree diagrams and equipment failure diagrams can all be useful diagrams to include. These additional diagrams will vary based on the MBSE tool, but may be used to provide a more robust structure and analysis of the system.

The addition of diagrams may not occur until later in the process, especially if embarking on new design efforts. Designs that draw upon familiar concepts previously used may have additional diagrams and tools considered, or even used, earlier in the process. It is important to consider if the diagrams used are effective at accomplishing the design intent and to make adjustments sooner than later to save valuable time.

Automobile Braking System Example: The next step is to develop the BDDs to provide a visual representation of the components and elements along with the interfaces and relationships shared with each other. The BDDs provide the logical hierarchical representation for the components of the brake system. The BDDs can be adjusted as necessary to provide the fidelity required for the design. Additionally, as the BDDs are more defined, additional diagrams may be needed that may require an additional tool to accomplish. The extent to which extra diagrams and tools are used is situational but should not be ignored if incorporation will be beneficial to the effort.

Step 5: Define data requirements and gather data

With the necessary diagrams made, the next step is determining the type of data needed. Data requirements can be defined based on the system, operating environment and/or mission set. The type of data determined to be needed may be failure rates, failure modes, operating temperatures, length of operation, etc. The data gathered must be adequate enough to accomplish the needs of the design effort. Gathering data is accomplished in a variety of ways. Historical data, field data separate simulations, data estimates or case study data are several ways that this step in the process can be completed.

Based on the design effort, the designers will determine the best data to use. Field data or Historical data is likely the best choice for an already existing design. It is important to note the characteristics of good data: accurate, complete, consistent, timely, valid and unique. Factors that would make this data less useful or nullify its use altogether would be system operation and/or environment is not consistent when collecting data and system being operated at different intervals during collection. The data gathered will be used for the next step.

Automobile Braking System Example: The data requirements now must be determined. In this example the, the realm of RAM analysis is the priority so the required data will consist of such data as failure and repair rates, availability, maintainability, and supportability. The Engineer will gather the required data from a historical database that is readily accessible.

Step 6: Make parametric diagram(s)

The Parametric Diagrams provide the basis for the necessary simulation and modeling for the design. It enables the integration between the design and analysis models through enforcing mathematical rules across Block Value Properties, which specifies the quantitative property of the block. The diagrams will be the basis for RAM value determination based on the data and constraints entered. A single or multiple Parametric Diagrams may be enough based on the modeling and analysis required. If a more robust analysis is required, the next step can be used.

Automobile Braking System Example: Once the data is gathered, the Parametric Diagrams will be made to provide the basis for the modeling and simulation required. The data will be included in the Parametric Diagrams with the required constraints and mathematical rules needed to get the desired results. Because RAM was the domain of choice using Monte Carlo simulations, the simulations will use the values from the BDDs, Parametric Diagrams and Cameo Simulation Toolkit to get the desired results. The output of the results can be shown in various forms such as a histogram, mean values, Component pass/fail, etc.

Step 7: Determine RAM values from parametric diagram(s) and compare to requirements

The RAM values can now be determined from the equations stated in the Parametric Diagrams and compared to previously defined requirements. The comparison of the values to the requirements is crucial to the design effort. The comparison may not be completed automatically, depending on the tool being used. If that is the case, the Engineer will need to check the results against requirements through an in-depth look at the results and the desired values. It is important to note that if additional components are added, the user must identify the relationships and include in the appropriate equations as necessary. Otherwise, the additional components will show in the diagram but not included in equations to calculate results. If the values are not consistent with what is expected or are determined to not provide the intended value to the design effort, then reconsideration of previous steps is required. The ideal place to start the reset is based on the results of the comparison analysis, but should return to Step 3 and continue through the steps again and make changes based on the analysis.

This process is intended to provide a framework to get from design concept to descriptive and logical system and subsystem states. The emphasis on proper tool selection through an analysis of Modeling Language, Structure, Modeling Process, and Presentation Framework will make it easier for the designer to create the BDD and Parametric diagrams while also showing the appropriate relationships and requirements. As stated in Step 4, the designer can use additional, better equipped tools as needed to provide more detailed models and simulation results for analysis.

Automobile Braking System Example: The calculated values will be compared to the requirements. If these values do not match expectations, the Engineer will determine where the gaps are and start again at a previous step and proceed through the methodology again. For example, if the final values are missing the analysis of a metric, the Engineer can go back to Step 3 and adjust or add data requirements, then resume from that step.

CHAPTER 4:
Illustrative Example of Methodology

This chapter will apply the methodology in deeper detail than the Automobile Brake Example in the previous section. The methodology will be applied to a Steam Turbine Fuel System and show the necessary tables, figures, and data needed. This chapter will conclude with a discussion of the results.

4.1 Illustrative Example Using Steam Fuel Turbine System

To effectively demonstrate the methodology, an illustrative example will be presented. The system this will be applied to is a Steam Turbine Fuel System. The turbines are driven by high pressure steam; produced when the flame in a boiler heats the high pressure water pumped into the system. The fuel system connected to this boiler uses natural gas to create the flame that heats the water to steam. Figure 4.1 below illustrates an example fuel system [56].

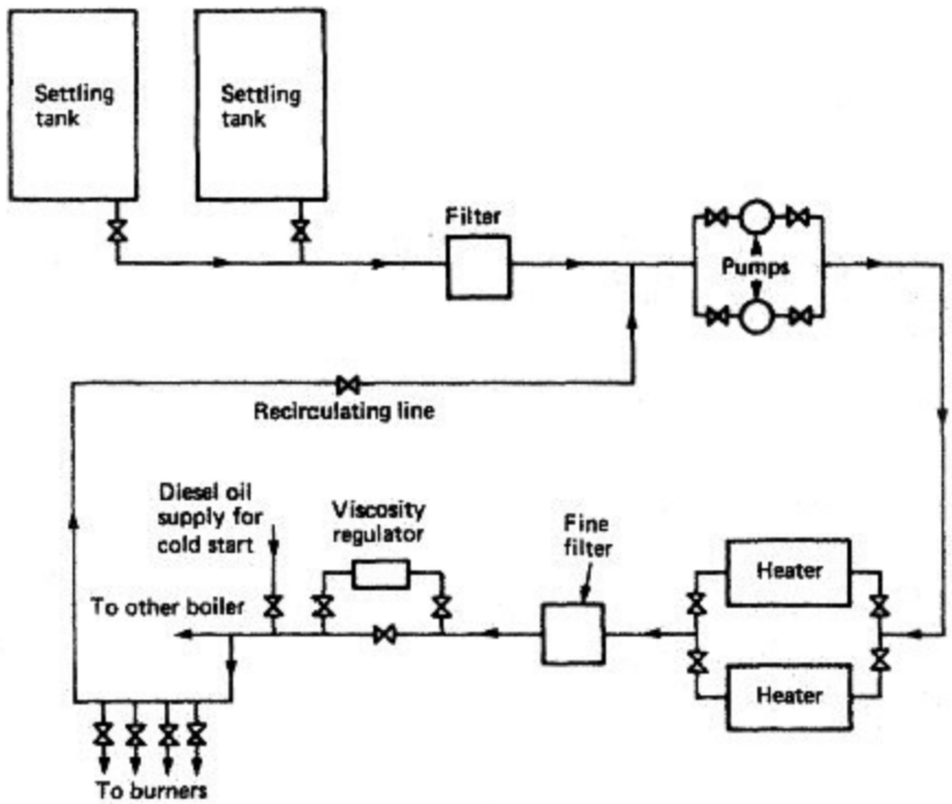

Figure 4.1. Fuel system diagram

The illustrative example presented is intended to show a likely scenario where this methodology will be implemented. The perspective will be from a Reliability Engineer tasked with satisfying the Need shown in Table 4.1. In addition to the Need to be satisfied, the Basic Flow, providing the background information and method for satisfying the Need, Subject Area and Trigger are shown.

Table 4.1. Reliability engineer requirements

Need	Determine Reliability of a Turbine Fuel System with Fault Tree and associated SysML diagrams. (3-out-of-4)
Basic Flow	A reliability engineer is tasked with determining the reliability for a Turbine Fuel System. The reliability engineer must also produce a Fault Tree and companion SysML diagrams that can describe component relationships with the overall system. The engineer will choose an MBSE tool (CEA) that will best describe the system. This tool will then be used to create the SysML diagrams to make the fault tree. A parametric diagram will be made in CEA to calculate the reliability of the system.
Subject Area	Reliability Analysis
Trigger	Determine Design Requirements of System

Using the information from the figure, the Engineer will be able to effectively conduct the necessary steps in order to successfully represent the system and implement the data in the model to get the desired results.

4.1.1 Step 1: Define for the design effort the modeling language, structure, modeling process, and presentation framework

The Reliability Engineer must determine the Modeling Language, Structure, Modeling Process, and Presentation Framework. Based on resources available, the Modeling Language selected is SysML, with the Structure and Presentation Framework selected determined by the organization to facilitate understanding of the content. The Modeling Process selected to run and evaluate the model is intended to create a series of hierarchical diagrams accurately representing the system and using those diagrams to inform the models being developed. Additional simulations can be run as necessary based on model needs. Simulations are ideal if experimenting on an in-use system is impractical or unable to be accomplished. Some primary drivers of choosing to incorporate a simulation are based on cost, time, and system configuration. A step-by-step method for simulation model selection and implementation exists, but will not be discussed in detail in this work.

4.1.2 Step 2: Select MBSE tool that can completely represent the system

Now that Step 1 is complete, Step 2's MBSE Tool Selection can be determined. The tool that can best represent the system and available to the Engineer is Cameo Enterprise Architecture (CEA). This tool uses SysML 2.0 as the Modeling Language and provides several diagram options to describe the system. Additionally, a Simulation Toolkit add-on is available to the Engineer to further improve the modeling and simulation capabilities should they be required.

4.1.3 Step 3: State system relationships/requirements

The RAM measures for the Turbine Fuel System are pivotal to the effectiveness of subsequent steps. There are many relationships that can be explored for the Turbine Fuel System; however, due to the complexity of Turbine Fuel Systems only a limited set are explored in this illustrative example. The requirements are listed in Table 4.2:

Table 4.2. Illustrative example requirements

Requirement 1	The reliability of the Steam Turbine Fuel System (3-out-of-4) shall be greater than or equal to 90%.
Requirement 2	The Availability of the Steam Turbine Fuel System shall be greater than 90%.
Requirement 3	Fault Tree Diagram shows accurate relationships of system components.

These three requirements will lay the foundation for ensuring the successful completion of subsequent steps fall in line with the desired product to be produced. It is important to note that while system relationships may evolve over the course of the design effort, the requirements for the design effort, in practice, are determined before this step. Requirements are included in this step to check that subsequent steps are in line with delivering the desired methodology output.

After careful consideration of the type of data available, equations will be selected. The equations selected will be used in order to determine Mean Time Between Failure (MTBF), Mean Time to Repair (MTTR), Reliability, R(t) and Availability, A(t) (4.1 - 4.5) [57].

$$MTBF = \frac{1}{\lambda} \tag{4.1}$$

$$MTTR = \frac{1}{\mu} \tag{4.2}$$

$$R(t) = e^{-\lambda t} \tag{4.3}$$

$$A(t) = \frac{MTBF}{MTBF + MTBR} \tag{4.4}$$

$$R_s = \sum_{x=3}^{4} \binom{4}{x} R^x (1 - R)^{4-x} \tag{4.5}$$

4.1.4 Step 4: Make block definition diagram(s) (BDD) and additional diagrams as needed

The BDD in Figure 4.2 shows the connections between the elements, components, systems, and subsystems within the Fuel Turbine system.

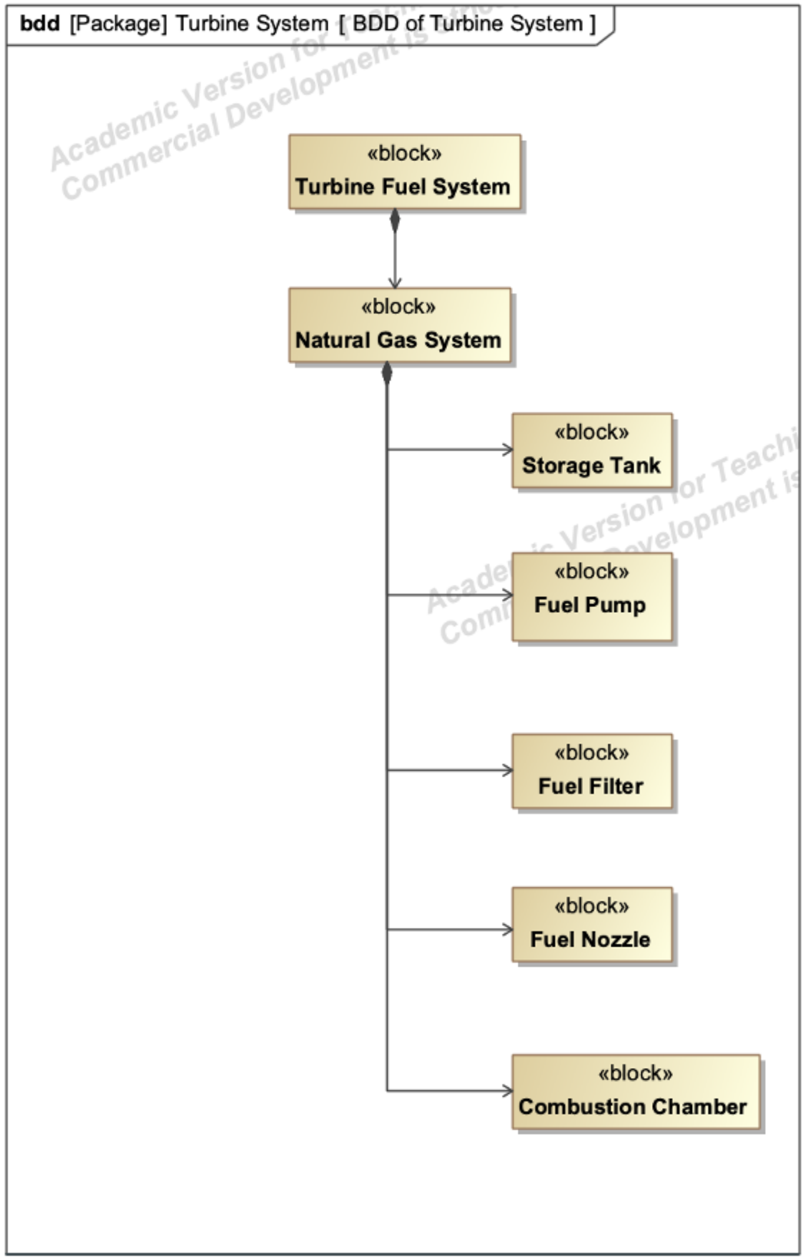

Figure 4.2. Block definition diagram of fuel turbine system

Figure 4.2 shows that the Turbine Fuel System is connected to the Natural Gas System. The Natural Gas System is then composed of five elements including the Storage Tank, Fuel Pump, Fuel Filter, Fuel Nozzle, and Combustion Chamber. The BDD shows the smaller systems that ultimately make up the Turbine Fuel System. Additional fault tree and equipment failure diagrams were included to provide additional information to show information on equipment failures for the system.

In the fault tree, the bottom level, light red boxes indicate the possible failures for the orange parent failure, connected by a greenish-gray AND gate. The light blue box indicates other possible failures for the Fuel System denoted by the gray box, connected by the purple OR gate.

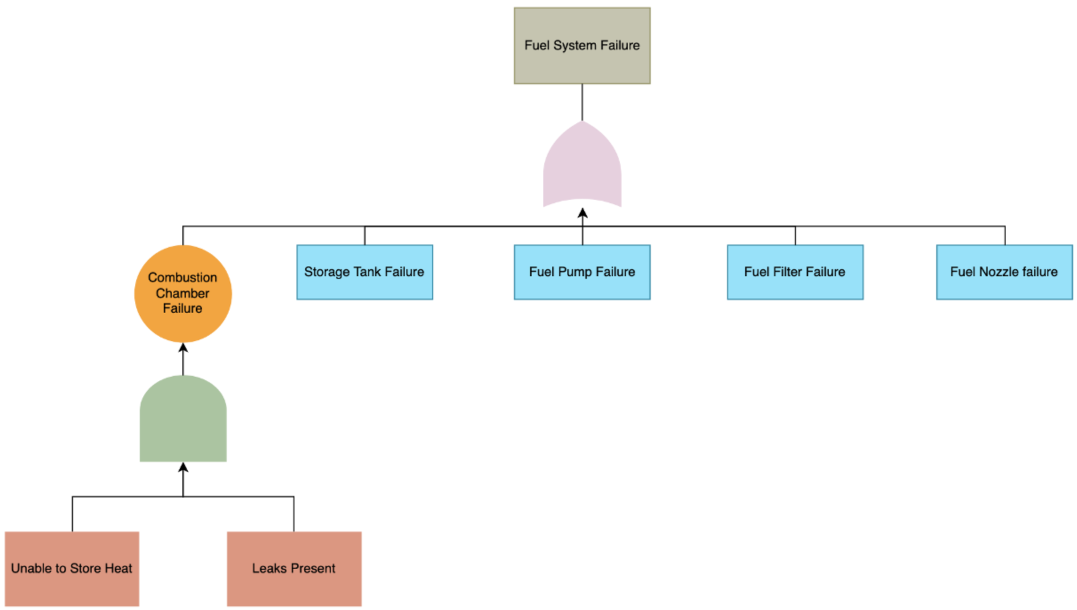

Figure 4.3. Fault tree of fuel system failures

Table 4.3. Equipment failures for fuel system

Storage Tank	Fuel Pump	Fuel Filter	Fuel Nozzle	Combustion Chamber
Corrosion	Contamination	Clogged	Contamination	Solenoid Valve Malfunction
Improper Construction	Overheating	Damaged	Improper Atomization Pattern	Clogged Main Burner Atomizer
Poor Maintenance	Wear	Incorrect Filter Type	Improper Nozzle Installed	Degraded Chamber Material
Excessive Pressure Due to Overfilling	Electrical Fault	Improper Alignment	Carbon Build-up	Holes in Chamber

Using external tools to fill gaps due to a lack of capabilities of the primary tool is expected. Should this issue occur, using additional tools to supplement work should be done as needed. Figure 4.3 shows a Fault Tree that was created using an external Web-based Tool to provide another visualization of the information and data provided. Figure 4.3 shows the types of equipment failures for the Fuel System. These figures provide amplifying information to those who may need it to understand system interactions and considerations.

4.1.5 Step 5: Define data requirements and gather data

The requirements for the data collection must provide sufficient information to determine RAM values for the system. Based on the equations used, the data information must contain the failure rates and repair rates for each turbine. The data is also verified as meeting the six characteristics of good data. Determining the requirements allows the Engineer to move onto the next step.

With the logical hierarchical diagram complete, the data for the system can then be gathered. For this illustrative example, the data was originally collected from an industrial turbine system [58]. Tables 4.4 and 4.5 illustrate this data:

Table 4.4. Collected historical data for year of 2015

Turbine Number	**Number of Failures**	**Repair Time (hours)**	**Operating Time (hours)**
T1	11	88	6471
T2	8	53	6509
T3	6	38	6526
T4	9	105	6456

Table 4.5. Failure and repair rates for year of 2015

Turbine Number	**Failure Rate** (λ)	**Repair Rate** (μ)
T1	0.0017	0.125
T2	0.0012	0.15
T3	0.001	0.15
T4	0.0014	0.08

The data presented is the necessary data for determining the reliability and availability of the Turbine Fuel System, using the equations presented in Step 3.

4.1.6 Step 6: Define data requirements and gather data

With the data now available, the Parametric Diagrams can be made that hold the equations and constraints to be used by the data. Figures 4.4 and 4.5 shown below illustrate the Parametric Diagram and its equations and constraints to determine the 3-out-of-4 Reliability for the Turbine.

With the data, equations and constraints now reflected in the Parametric Diagram, the Reliability and Availability values can be determined.

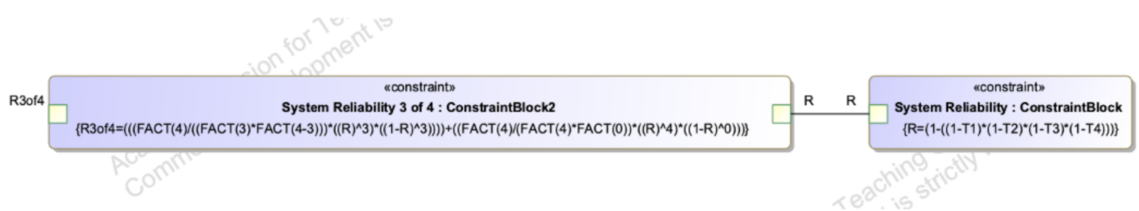

Figure 4.4. Parametric diagram of fuel turbine system showing 3 of 4 system reliability

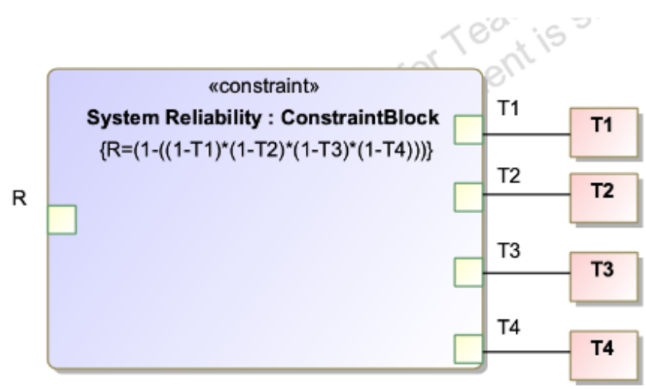

Figure 4.5. Parametric diagram of fuel turbine system showing system reliability with turbine inputs

4.1.7 Step 7: Determine RAM values from parametric diagram(s) and compare to requirements

The final step calculates the results and compares them to the requirements. The results are shown in Tables 4.6 and 4.7. Comparing the results to the requirements will determine how well the data selected and model chosen met the requirements. Should the results not match the expected values, then the Engineer will re-evaluate decisions made at a previous step. The most likely place to begin an analysis of potential pitfalls in initial requirements will be at Step 3 or 4, then resume the process from that step. The comparison is simple but a pivotal step in the correct implementation

Table 4.6. Parametric equation results

@time t	100 hours
3-out-of-4 Reliability	0.93
Availability	0.99

Table 4.7. Number of failures and associated states

No. of Failures	**Probability of Each State**
0-item failures	59%
1-item failures	34%
2-item failures	5%
3-item failures	1.8%
4-item failures	0.2%

4.2 Discussion

The primary benefits of using this methodology is it provides an easy to follow, streamlined process for incorporating MBSE and RAM techniques. Traditional methods are effective but can become cumbersome if certain factors are missing or lacking. By providing an basic methodology with specific information on what should occur in each step, the user has a road map for achieving the desired end results. This methodology is ideally implemented early in the design process with certain data assumptions being made. These assumptions can be made based on best estimates or if historical data for some or all components are available to be used. Having modeling resources available to conduct the required simulations is ideal. In practice, however, these values can be determined through other methods as well, such as Excel or other available reliability software to verify results. If results are different, the Engineer will likely review the Parametric Diagram equations for possible errors in calculations. The final step in which the comparison is conducted is a simple, but pivotal step in the correct implementation of the methodology.

The methodology presented is intended to provide a basic blueprint for developing RAM models that can be integrated into a MBSE environment. Following the steps in order provides the best chance for saving time and potential for rework, lowering cost and scheduling overruns on the project. Beginning with Steps 1 and 2, the primary drivers in the MBSE realm are determined and selected based on the design needs. Stating the system relationships in Step 3 shows how the different parts of the system interact. Step 4 is informed by the relationships and the effective creation of BDDs and other diagrams as needed. The incorporation of additional tools as necessary to add additional data or information should not be ignored, despite the increase in time required to use effectively. If initial MBSE Tool selection is limited in certain aspects, the incorporation of other tools and time to gain proficiency, if not achieved already, should be accounted for to provide the best long-term chance for success.

Defining data requirements, gathering the data and ensuring their quality, provides the foundation for getting the desired results needed for analysis. Making and evaluating the parametric diagrams and comparing to requirements incorporates MBSE and RAM techniques, culminating in usable information for the Engineer to make a decision on the design process. The comparison is critical for checking the process of the design effort and determine if a single step or multiple steps need to be readdressed to the desired degree.

A drawback to this method is if a user has to make many detailed diagrams and switch between MBSE tools, the expectations for what should be accomplished in which tool may become fuzzy. If, for example, a user needs to switch between tools in order to generate various diagrams, they may find that the additional tool provides better capabilities than the original tool. This realization can happen due to a number of reasons, and may end up causing the user to second-guess the originally selected tool. To save time and effort, adequate time should be spent in Steps 1 and 2. If a permanent change should be made to make the additional tool the primary tool considerations such as time needed to move information, such as data and diagrams, should be considered before making the change.

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CHAPTER 5: Conclusion and Future Work

This chapter explains the conclusions as a result of the applying the methodology. In addition, an exploration of possible areas of study for future work is described and its applicability to current areas of study.

5.1 Conclusion

The intent of this research was to provide a methodology that could be applied to design efforts. A literature review was conducted to ascertain the amount of work that currently exists in the realm of MBSE and RAM integration. The review also serves as a way of gaining adequate background information to inform the development of the methodology. Following development of the seven step methodology, an example was provided. This example was provided in two ways; first, through a walk-through of each step for an automobile brake system, then through the application as a part of an illustrative example for a Steam Turbine Fuel System.

The illustrative example demonstrates the validity of the methodology and how it can be used for a design effort. A particular gap that exists for this method is in the realm of tool selection, namely, if multiple tools are to be used. Switching between tools constantly can cause issues in several areas, such as diagram generation. While a possible pitfall, an understanding of what should be done based on the tool used is the best way to ensure the needs of the effort are met based on the tool.

5.2 Future Work

Areas of interest for future work should be to determine the changes necessary to better suit this methodology to new design efforts for which minimal or no data is available. This would provide two different methodologies, each with its own set of characteristics and uses. The application of this methodology to a new design would be the best way to determine its feasibility.

Further areas of interest for future work would be determining a methodology for using multiple tools at once and seamlessly transitioning between those selected. As systems become increasingly complex the ability to transition between multiple tools may be needed. Utilizing the advantages of these various tools simultaneously while following the methodology presented in this thesis or an adaption of it, ha the potential for being incredibly beneficial.

The method presented in this thesis used a specific tool and modeling language. Determining the effectiveness of the methodology presented in this thesis using a different tool or modeling language would be beneficial in demonstrating a more universal application of the work. Additionally, determining the feasibility of this method when incorporating multiple system models across various languages and tools would be beneficial when applied to system designs that are significantly complex.

Lastly, research into what changes should be made to make the method presented better suited for wider application and distribution as a whole, regardless of tool or modeling language is of great importance to further refinement and efficacy of the methodology. Being able to apply different frameworks and modeling processes can have significant impacts on the steps of the methodology and in what design conditions it may be better suited. These areas for future research would expand upon the current work done in a meaningful way. This methodology would be tested in various conditions not touched on in the current work which would provide further refinement to the methodology presented.

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