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# Implementation of MBSE Approach for Developing Reliability Model to Ensure Robustness of Sounding Rocket Program Using MADe Modeling Tool

**T Odita, MJ Louise-Caballes, and G Chen**

Morgan State University
Baltimore, MD, USA

Corresponding author's Email: toodi1@morgan.edu

**Abstract:** NASA Sounding Rocket Program (NSRP) is a research-based program that heavily targets relevant institutions to conduct studies for atmospheric research in space. The program has been operating for over 40 years. NASA's goal is to use Sounding Rockets to allow colleges and universities to carry out scientific research missions, particularly low gravity, and material-based research. Due to the Sounding Rocket's complexity, the implementation of a Model-Based Systems Engineering (MBSE) approach was utilized in both functionality and capability to generate a model-based systems diagram and provide a robust design for reliability, risk, and safety. Through the MADe tool usage, both Failure-Modes-Effects and Critical Analysis (FMECA) and Fault Tree Analysis (FTA) was designed and evaluated. The specifications of the rocket's fuel flow and engine were used as the basis of the study and how it affects the Systems Development Life Cycle (SDLC) of the Sounding Rocket. Whereas, the generated model-based system diagram can be used for risk assessment, to identify the possibility of failures and causes and critical errors that may affect the reliability of the Sounding Rocket. Through the MBSE approach, this research can bridge the current gap by utilizing MADe as the primary modeling tool to develop and design a model-based systems diagram to meet the current needs of Reliability Engineering within NSRP and Safety and Mission Assurance (SMA).

*Keywords:* NASA's Sounding Rocket Program (NSRP), Model-Based Systems Engineering (MBSE), Failure-Modes-Effects and Critical Analysis (FMECA), Fault Tree Analysis (FTA), Maintenance Aware Design Environment (MADe), Systems Development Life Cycle (SDLC)

## 1. Introduction

Systems Engineering (SE) is a widely known discipline that focuses on the overall development of a system. Aside from managing and overseeing the whole System Development Life Cycle (SDLC), it is also the one that is accountable for uniting the vital elements in a project into one overall system throughout its lifecycle. By establishing a SE process in a project, it can quickly provide a structural approach for solving problems, efficiently track requirement flows via design effort, modeling tools, unified modeling language, and object-oriented programming – to name a few, as illustrated in Figure 1.

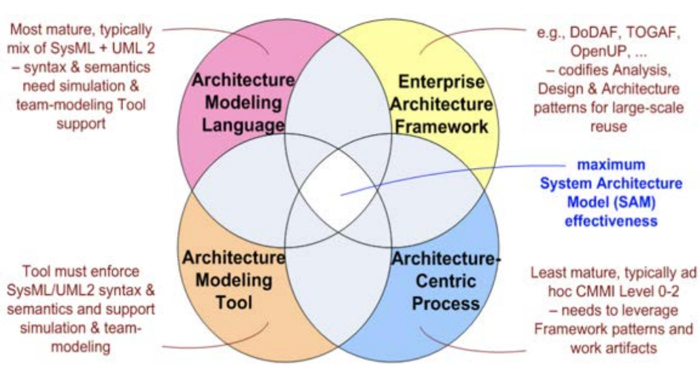


Figure 1. MBSE System Architecture Tetrad (PivotPoint Tech Corp, 2003)

One of the primary methodologies that systems or software engineers widely use is a Model-Based Systems Engineering (MBSE) approach, especially if they seek an efficient and effective model-driven process. MBSE methodology provides Mission Assurance (MA) opportunities to move from a document-centric approach to an objective-based product (Dori, 2016). With this, the results increase efficiency and contribution during the timely conduct of assurance activities. Thus, making it a robust approach in SE. Furthermore, during the design phase of a system, data will be evaluated and meticulously captured to be analyzed, queried, validated, and transformed. The modeling approach of MBSE takes advantage of model-based systems diagrams to stipulate the system readily.

Along with the benefits, MBSE can assist in three methods, which are (1) address intricacy, (2) urge reuse, and (3) manage product lines. Complexity is usually the source of systems engineering obstacles. By utilizing a visual representation of the system, both connections and interactions between various systems are much easier to see (Hart, 2015). The MBSE model will sustain the layout, analyze confirmations, and validate the entire system. Furthermore, the model gives a standard reference across engineering disciplines to ensure that other groups will quickly interact and collaborate during the development cycle of the design, but it also enhances the communication results to better effectiveness. Besides, since the system design makes it less complicated to visualize the system's interdependencies, the risk of having mistaken and a possibility of critical errors also decrease, especially when making changes. Similar researchers explored a methodological approach of MBSE and used UML, SysML, and MARTE modeling tools to solve complex systems (Rashid et al., 2015). By following this approach, MBSE can quickly identify the structural and behavioral aspects of the modeled system (Lee et al., 2017). Figure 2 shows the MBSE methodology framework and how it carries out the verified activity to accomplish and assess the correctness of the model/system. Also, the two conventional transportation approaches are (1) Model-To-Model (M2M) and Model-To-Text (M2T). As observed in Figure 2, the model system's execution will recognize the alterations to correct if there is an error after Model Transformation and through simulation. The International Council on Systems Engineering (INCOSE) identifies MBSE as a formalized application of modeling to assist system's demands, design, validation, evaluation, as well as verification activities, beginning in conceptual style phase, proceeding throughout development, and later on the SDLC (Kaslow et al., 2014). Whereas, the NASA Systems Design Handbook defines MBSE as a durable strategy for the design, creation, and operation of systems. Additionally, after capturing the information regarding a system, it can be examined, inquired, confirmed, and transformed into another form for further processing (Bijan et al., 2011; Hoffman, 1995).

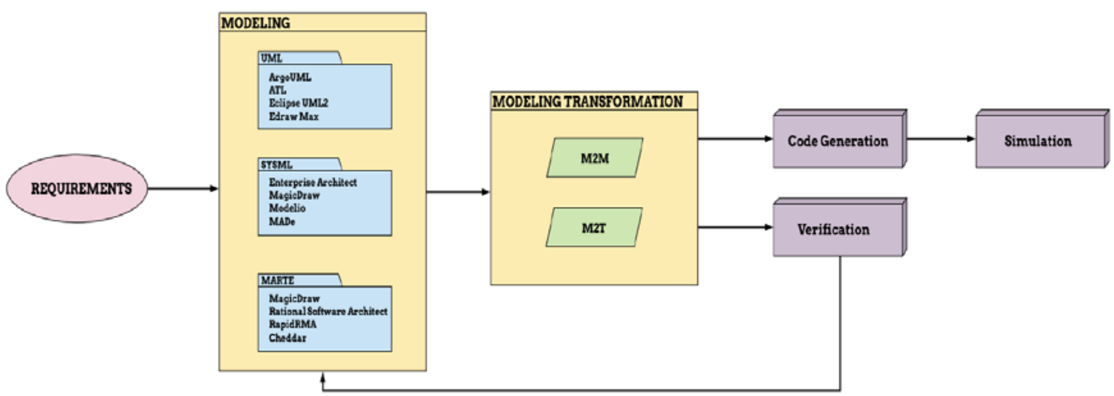


Figure 2. MBSE Activities for Embedded Systems (Anwar et al., 2017)

A rigorous MBSE is easily achievable by defining the conceptual models, languages, standards, tools, and processes. Both theoretical and conceptual models deliver a strong vocabulary for systems engineers to process data with precise and accurate meaning (Chen & Meli, 2017). Through this, it will undoubtedly cause creating uniformity throughout modeling artifacts (i.e., requirements, user interface needs, system analysis, design, and examination strategies). Making use of industry-standard enables the embedding of the robust vocabulary into a graphical modeling language. Techniques and processes help the system engineers establish a model using SysML and permit the engineer to concentrate on domain name problems (Karban et al., 2014). Several studies tailor the NASA's Sounding Rocket Program (NSRP), located at Goddard Space Flight Center (GSFC) in Maryland, due to its complexity in both modeling and simulation (Waldram et al., 2019; Holladay et al., 2019). Figure 3 shows the overall systematic components of a Sounding Rocket. SE experts in GSFC provided various MBSE application cases and structural environment models of the Sounding Rocket's sub-systems, which led to a consistent, accurate, and efficient process (Lindsey et al., 2020). It was only in 2011 when the engineering community in NASA started assessing an electronic strategy's ratification and fully embraced both functionalities and capabilities of an MBSE approach to the Sounding Rocket program. In 2016, NASA's spaceflight and rocket systems skyrocketed due to the MBSE approach's implementation and its deterministic process in evaluating and addressing its critical and most challenging aspects. Since then, the application of MSBE continually expands to even more rigorous demands throughout the several stages of the systems engineering lifecycle (Holladay et al., 2019). Thus, it resulted in over a dozen concrete application cases that illustrate the benefits of a digital framework for systems engineering.

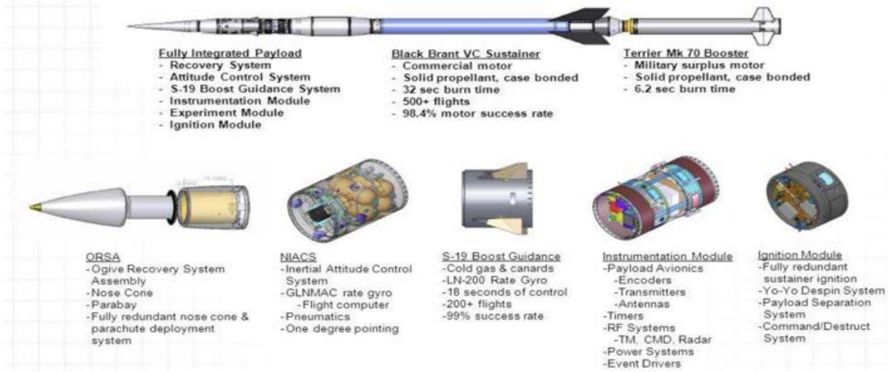


Figure 3. Sounding Rocket System (Chen & Meli, 2017)

This research's main objective is to develop a reliable and safety modeling framework using the MBSE approach for analyzing large-scale and complex systems in NSRP through the usage of the Maintenance Aware Design Environment (MADe) tool. The NSRP is a sophisticated program with a wide variety of variables and data that characterize an NSRP project's advanced phases. Currently, there is no consolidated System Engineering process for Reliability Engineering within NASA's Safety and Mission Assurance (SMA), taking into consideration risk, safety, and quality assessment. Numerous methods had proposed to address this issue. Probably the most prominent of them is the MBSE approach, which stands and is useful for Reliability Design for NASA's SMA. This research seeks to bridge the current gap by utilizing MADe as the primary modeling tool to develop model-based systems diagrams and meet the current needs of Reliability Engineering within NSRP and SMA.

## 2. Methodology

### 2.1 Sounding Rocket Mission Acquisition Life Cycle Models

The NSRP is an ideal project and opportunity for the respective SE experts in the field and the multi-disciplinary students, researchers, and engineers. NASA's Sounding Rocket carries experiments to altitudes between 50 and 1,500 km and flies nearly in parabolic trajectories (Weiland & Holladay, 2017). Thus, through the utilization using the MADe modeling reduces both liabilities and uncertainties in a complex system. Its primary usage is to enhance the process by improving the system's accessibility in architectural framework development by combining models with analysis to enable trade studies on the safety, reliability, and maintainability of complex engineering systems. MADe is a software application device that helps systems engineers develop a model-driven architectural design of components, systems, and subsystems. Thus, this will help in determining potential issues that will profoundly affect the reliability of the system.

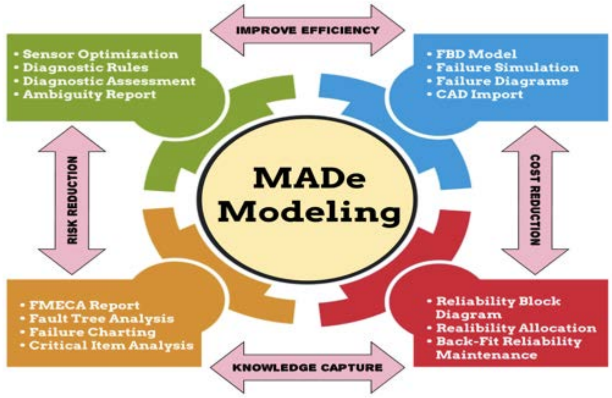


Figure 4. MADe Features and Systems Applications

Figure 4 shows the features and system applications used by using the MADe modeling tool. Through the utilization of this modeling tool, it can efficiently generate and create model-based designs that show risk reduction, knowledge transfer and capture, and efficiency of the Sounding Rocket. In this research, the implementation of MBSE in aerospace applications plays a vital role since it has both capability and functionality to design and evaluate Failure-Modes-Effects and Critical Analysis (FMECA) and Fault Tree Analysis (FTA). This approach can only be possible in developing the Reliability Block Design because of the tool's reliability and availability analysis function (Odita et al., 2019). Additionally, during the development of the heuristic model-based approach, a total of three main functionalities which are the tool's ability to present the data into pre-formatted reports, the capability to condense the information from multiple platforms into a single file, and the versatility and ease of use were considered to support the said notions. The MADe tool offers a specific analysis of workflows for both dependability and reliability. It consists of Reliability Allocation, Reliability Block Diagrams, Markov Analysis, and Reliability/Availability Analysis with numerous failure circulation approach to produce and confirm the reliability requirements for each phase of the system's design process. These analyses allow for an on-demand generation of FMECA and FTA.

## 3. Results and Discussions

### 3.1 Failure-Mode-Effects and Critical Analysis (FMECA) Model

The Power Generation was used as part of the data function during the failure diagram modeling to produce electrical power to areas where utility electricity was unavailable. Figure 5 shows a specific failure diagram modeling of a Sounding Rocket's fuel flow plumbing. This fuel draws diesel or gasoline engines to provide torque output controlled by a continuous signal from a control unit. Three potential effects are essentials to be observed in the Part-Pairs Failure Diagram Model: damaged surface protection, corrosive contaminant, and maintenance actions (Odita et al., 2019). These potential errors originate by the faulty inlet lining and eventually lead to an acid attack on the inner surface. The modeled Part-Pairs Diagram is a pair-specific failure model that contains the information of functions and elements, which then declares the starting phase of the Functional Block Diagram (FBD). Unless the part failure diagrams are constructed similarly to component failure modes, it continually connects to another section until the failure path ends at fault due to the parts unable to fulfill their designated functions. Nonetheless, two elements together can form a pair whose function can easily be defined and determined.

When modeling conceptual designs that have not yet defined in terms of their solutions, requirements, and specific elements modeled a generic failure diagram as a nonproprietary component. However, the failure diagram must still be modeled based on its functional output's expected response without referencing the physical processes of failure or hardware degradation. One of the advantages of using the MADe software when creating model-based systems diagrams is its functionality to input the relationship between various inputs and outputs of the different subsystems and its paired components. Moreover, figure 5 also illustrates the relationship function that shows how the model was established by choosing targeted critical criteria in a Sounding Rocket engine's fuel flow. Additionally, the input and output flow for creating an FMECA Model selected both Flow Rate and Static Pressure. In MADe modeling, the streams are connected internally through causality. The input pressure-flow entering the valve determines the flow rate output of the liquid flow exiting the valve. Externally, both input and output flows are connected to one model item to another, since the valve's output flow rate connects directly to the pump component's input flow. Nonetheless, it is crucial to thoroughly assess these functions adequately since the input and output flows connect through the internal causal linkages and throughout the system.


Figure 5. Part-Pairs Failure Diagram with FMECA Modeling (Odita et al., 2019)

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### 3.2 Failure Diagram Mapping

The flow properties are the defining categories during the creation of the FMECA Model. These properties represented the functional requirements of the Sounding Rocket's components and were used to define its function and functional failure modes. In the input data, the flow categories' specifications are solid, liquid, and gas flow were declared. Furthermore, each specification has its unique data due to its difference in both heat and temperature flow. The input flow properties re-linked to output flow properties using a causal connection to ensure that an injected failure during a failure simulation analysis can propagate throughout each component and elements. The failure diagram maps out the sequence of events leading to an items' functional failure mode. Figure 6 shows a graphical representation that shows the mapping phase of modeling a Failure Diagram.

When the liquid flows to the engine of a Sounding Rocket, inevitable failures might happen. They will have a chain of causes that will profoundly affect the system's performance and mechanisms, leading to a system failure. However, due to the parts' characteristics, it will only perform when the functions connect in pairs or when individual components cannot connect through the input. Thus, the functions were defined and determined during the operation of the item and the required data. If a failure occurs, the system will generate an appropriate solution along with the FMECA Report.

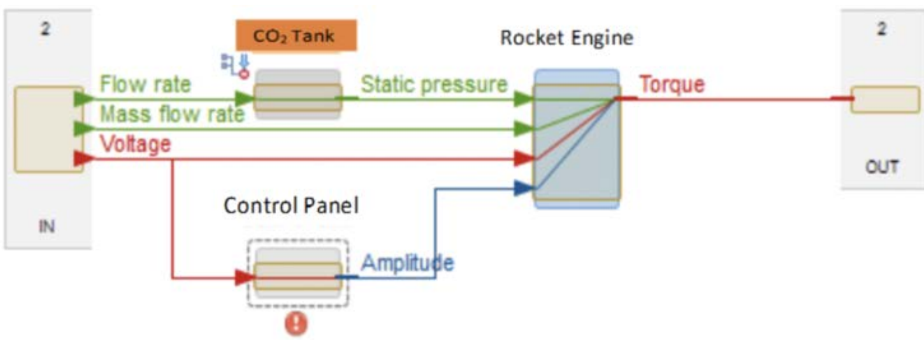


Figure 6. Failure Diagram Mapping (Odita et al., 2019)

Furthermore, the figure also illustrates a generated Failure and Functional Model after mapping the Failure Diagram's inputted components. The model shows a graphical representation of the sequence of events that will fail based on the input data from the FBD. One of the MADe modeling tool's attributes provides a comprehensive collection of different varieties of mechanisms composed of elements, parts, data, and functions. Furthermore, by defining the workflows of the system's functional requirements first, it generated a Failure and Functional Model that provides the overall functionality of the whole system and foretells the possibility of failure of the Sounding Rocket's subsystems, components, and parts (Odita et al., 2019).

### 3.3 Failure Functional Model

After creating the necessary items such as the subsystems, components, and parts, both the system functions and flow rates of the Functional and Failure Model require constant checking and validation in determining if the functions were able to capture the data correctly. Thus, it will generate a unique model algorithm that serves as the foundation of the Failure Model Diagram. Furthermore, since the created model is basing on the data specifications of both components and elements, it provides a more accurate result (Odita et al., 2019), which makes it a more and reliable tool during this research study. Moreover, it is worth noting that the MADe automatically generates the flow rate connections of the system's internal flow during all indenture levels for both components and subsystems. Figure 7 shows that the system flow represents a dashed line connection in the upper area's functions model.

Figure 7. Failure and Functional Model (Odita et al., 2019)

The red circular icon displayed in the modeled Failure diagram represents the components of the Functional and Failure mode (output flow property), which are the couple, mechanical, rotation, and angular velocity. This icon cannot be removed or changed unless the function, flow, and flow property of the item in the function editor are either removed or modified. Moreover, the trivalent thresholding is the default failure simulation threshold set in the MADe tool. The threshold type assigns three possible states to a functional failure mode – Low (Flow fails Low), Nominal (Flow is Nominal), and High (Flow fails High). This approach will determine whether the failure mode results in one of the failures states during analysis and the failure path (i.e., the sequence of events) leads to a failure diagram, and thus mapping out the functional failure mode first. Thus, this can only be done by connecting failure causes, mechanisms, and faults to the functional failure mode. The failure concepts are defined in MADe using a standardized taxonomy of failure concepts.

## 3.4 Fault Tree Analysis (FTA) Model

A breakdown of the Sounding Rocket's synthetic stages can easily be provided by generating an FTA Model. Figure 8 illustrates a top-down deductive failure analysis model that shows an undesired state of the Sounding Rocket's systems and is analyzed using Boolean logic to combine a series of lower-level events to reduce the risk of a system's failure or determine the possibility of event rates of safety accidents. As observed in the model, the Control Process serves as the peak of the generated FTA of the Sounding Rocket. It implies that the most crucial component in the Sounding Rocket's system is the Control Process/Center since it manages and controls the overall flight from the point of launch until landing or the end of the mission. Additionally, the generated FTA's conditions from MADe will automatically classify and arrange the components by their effects. The most severe condition requires the most extensive FTA. The given model also shows how a Control Process failure will have a chain of effect in the command uplink, airborne computer, telemetry interface, star tracker, tank, plumbing, and valves. Through FTA, it can efficiently provide insights about the reliability analysis of a Sounding Rocket that complements the usage of Reliability Block Diagram. Thus, generating an FTA Model renders invaluable visual aid representing the breakdown of errors and possible failures from the highest system level to the lowest component level.

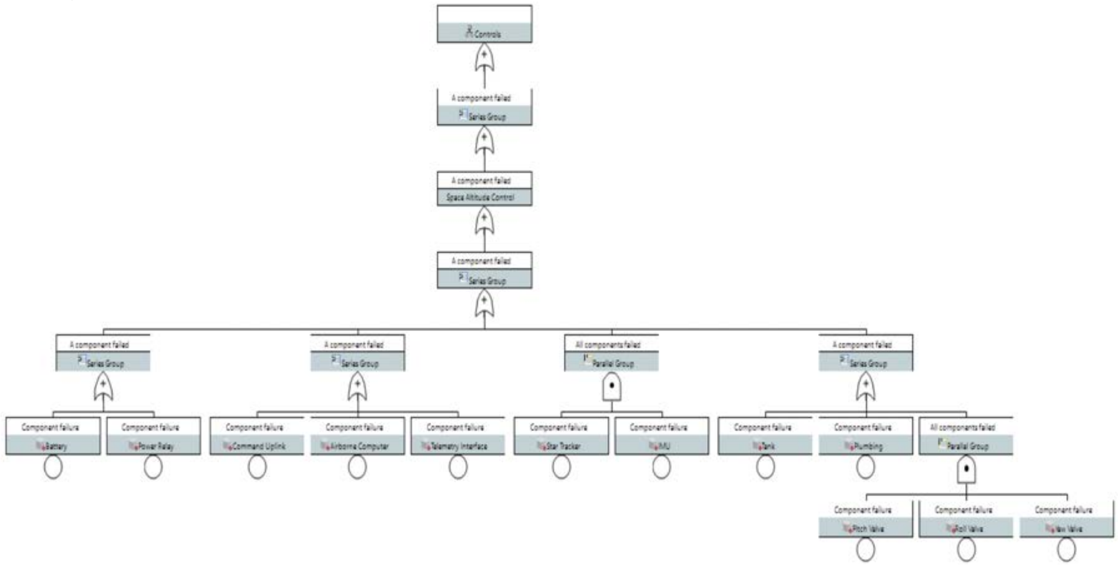


Figure 8. Fault Tree Analysis Model Diagram (Odita et al., 2019)

## 4. Conclusion

In conclusion, using an MBSE methodology in the aerospace application can efficiently provide a paradigm approach that utilized a model-based diagram throughout the SDLC. This research was able to achieve the objective, which is to develop a reliable and safety modeling framework using the MBSE approach for analyzing large-scale and complex systems in NSRP through the use of the MADe tool. The tool quickly generates the FBD models of FMECA and FTA based on the Sounding Rocket's parts and components' inputted data. Additionally, it records and automates the increase in identifying possible failures and critical errors of the Sounding Rocket. The FMECA shows consequences in the functional model on the operation, function, and system status. Thus, it resulted in a failure path in the failure diagram.

Furthermore, the failure diagram of the Sounding Rocket's plumbing failure shows how it will eventually affect the engine's torque outputs, causing three potential effects that can damage the surface protection, corrosive contaminant, and maintenance actions. Furthermore, using the MADe tool can provide the relationship function that illustrates how the model is established by choosing critical criteria in sounding rocket engines' fuel flow. As stated, the created FMECA Model defines the possibility of failures of the flow properties, precisely the specification of flow categories – solid, liquid, and gas flow. Moreover, the Failure Diagram's output shows the possibility of the critical failure of the components, including the couple, mechanical, rotation, and angular velocity. Moreover, it also determines the functional models – Low (Flow fails Low), Nominal (Flow is Nominal), and High (Flow fails High). Lastly, through the MADe tool, a Fault Tree Analysis was generated and organized for reliability analysis of the Sounding Rocket in a hierarchically ordered – lower-level to high-level process.

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