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Application of Model Based Systems Engineering in Aerospace Case Study by Using MADe Software

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Synopsis:

In this project, two MSU engineering students are engaged in the investigation into the application of MADe (a reliability and systems engineering study software) to spacecraft subsystems development, under the guidance of Dr. Chen and NASA reliability engineers at Goddard Space Flight Center. The goal is to apply the software in the subsystems development of spacecraft such as sounding rockets in order to improve the process efficiency and understanding between various subsystems groups.

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Abstract

Model based systems engineering (MBSE) is an effective tool to enhance the efficiency of a large project, especially in aerospace industry. The risk and reliability engineers at NASA Goddard Space Flight Center are interested in using MADe (a MBSE software tool) in the subsystems development of spacecraft to improve the risk and reliability study. In this study, two engineering students from Morgan State University (MSU), supported by a space grant, are engaged in using MADe and system functional block diagrams to reduce the risk of inconsistencies in reliability studies among reliability engineers and systems engineers. The goals of the study are: 1) to use MADe to build a library of common spacecraft subsystems and components; 2) to develop the standardized formats for the reliability assessments, relate them to systems engineering models, and verify that they are consistent with each other. To achieve these goals, we have developed two models, the spacecraft propulsion and sounding rocket systems in order to generate the reliability analysis. These models are necessary because it provides the study with an intermediate step between transitioning from the models to the reliability analysis. In these models, multiple tasks, such as constructing failure diagrams, are performed to determine the severity of the failures. One key finding of the study is that we are able to generate the desired reliability analysis with modifications and needed adjustments in order to meet NASA standards. Another important finding is that we are able to broaden the scope of describing and understanding component failures and faults. In conclusion, using MADe tool in conjunction with the functional block diagrams is a good step in right direction because of the software's vast potential and the excellent support received from the MADe software developers. This interesting exercise has also engaged MSU students in spacecraft subsystems development case study.

1. Introduction

The Maintenance Aware Design environment, or MADe, is a model-based systems engineering tool that presents the user with the ability to generate several reliability analyses from multiple engineering disciplines into a report format (MADe module user manual: Functional modeling and failure definition, 2017). This tool currently has three modules that focuses on other aspects besides building the model: Safety & Risk Assessment (SRA), Reliability, Availability, & Maintainability (RAM), and Prognostics & Health Monitoring (PHM). For this study, the research team decided to only use the SRA and RAM modules. The deliverables are the successful generation of several reliability analyses and two new models to be added to of a new aerospace library.

MADe is a software tool used by engineers to model parts, components, sub-systems and systems in order to identify and assess potential functional and safety issues in the system design (Failure Mode and Effects Analysis or FMEA). MADe can be used at all stages of the design process (conceptual, configuration, detail, technology refresh, upgrade) and was developed for complex, integrated, multi-domain systems (mechanical, hydraulic, electronic).

The MADe modeling tool is quite beneficial for aerospace application. One important field impacted by the modeling tool is design and safety, where the reliability analysis of FMEA (failure mode and effects analysis) and FTA (fault tree analysis) are applied extensively. Another significant application is reliability and availability analysis, which employs the RBD (reliability block design). Fortunately, there are several additional factors that support the above-mentioned notion. The first factor is the ability of the modeling tool to present the data into pre-formatted reports. The second factor is the capability of the modeling tool to condense the information from multiple platforms such as Microsoft Excel into a single file which can reduce the failure rate due to human error. The third supporting factor is the versatility of the modeling tool due to the potential application in various industries such as car manufacturing and product design. The final factor is the access to vast resources such as user manuals and libraries that have expedited the learning curve.

2. Research Goals

The main focus for the research tasks assigned to MSU team by NASA risk and reliability branch is to determine whether MADe modeling tools with reliability and systems engineering capabilities can be applied for future NASA missions. The first research goal is to start the process of creating and updating to a new library of general spacecraft components and subsystems with the previously completed reliability analysis as a reference. The second research goal is to determine a way to easily generate multiple reliability analyses that have a preformatted and ordered layout, and smoothly expand to systems engineering without any inconsistency. To achieve the second research goal, the MSU team uses the MADe modeling tool’s capability to automatically display the information from the model into specifically organized reports for FMEA, FMECA RBD and FTA reliability analyses.

3. **Building Models**

3.1 Real Life Applications

In order to be able to accurately evaluate the MADe modeling tool for the Aerospace field, the team decided to model a Spacecraft propulsion system and a Sounding Rocket system. The Spacecraft propulsion system had several major components with a high level of variety. In figure 1, there were multiple tanks, valves and filters for pressurization and propellant, and four thruster clusters. This diverse collection of parts provided the system with an excellent chance for a high success and low failure rates.

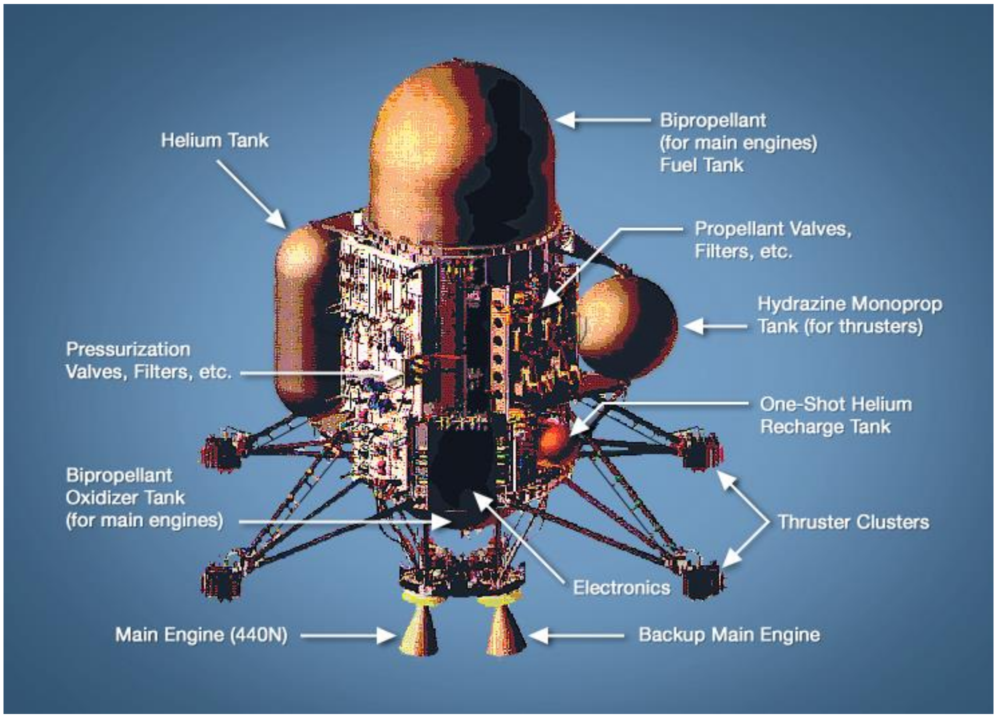


Figure 1: Spacecraft propulsion system (Shekhtman, L., & Thompson, J., n.d.)

The Sounding Rocket system was more complex and larger than the Spacecraft propulsion system due to the vast amount of functions that were needed in order for the system to run smoothly. In figure 2, the Sounding Rocket system must be able to not only launch successfully, but be able to change altitude at will, communicate internally, communicate externally, conduct experiments, and collect data.

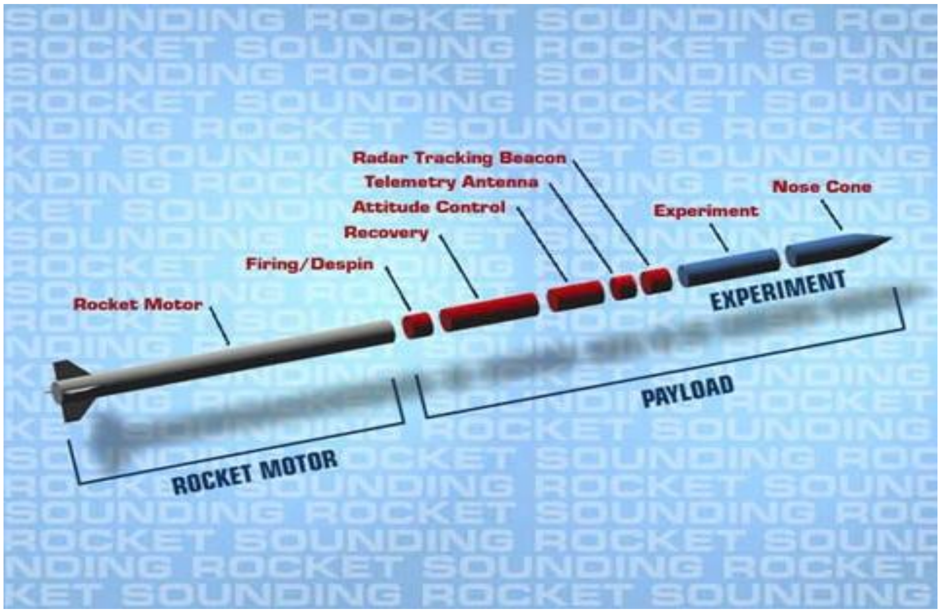


Figure 2: Sounding Rocket system (Marconi, 2007).

3.2 Schematic Diagrams

The next step in the study was to create schematic diagrams of the two systems. Schematic diagrams are extremely helpful at the beginning stages of this study because it is essentially one of the first visual representations or blueprint of the model. In figure 3, the schematic diagram of the Spacecraft propulsion system prepares the team to transition from the planning stage to the modeling stage of the project.

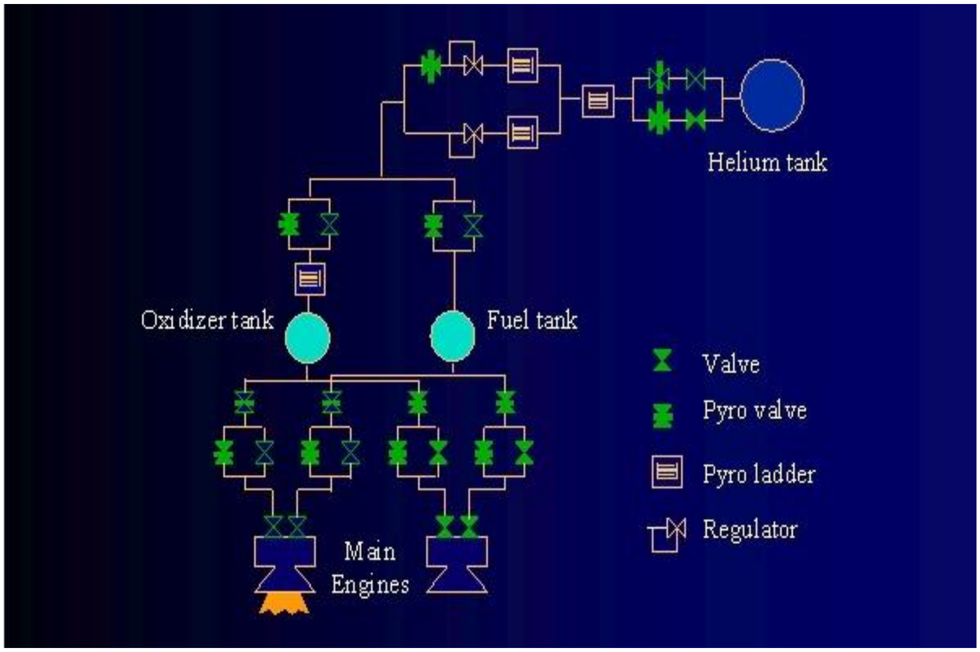


Figure 3: Schematic Drawing for Spacecraft propulsion system (Williams, B., & Nayak, n.d.).

There were several changes from the real-life applications to the schematic diagrams to the MADe models shown in figures 4 and 5. For example, in the Spacecraft propulsion system, the tanks were renamed as oxidizer or fuel tanks while the valves were labeled as latch, pressure control, or service valves. Due to the before mentioned high complexity of the Sounding Rocket system, the team decided to choose one out of the numerous levels available so that the focus can remain on evaluating the tool. For the chosen level, the Payload sub-system, the experiment was renamed as the data collector, recovery as parachute, and telemetry antenna as transponder. For the remainder of the research, the features of MADe will be using the transponder component as an example.

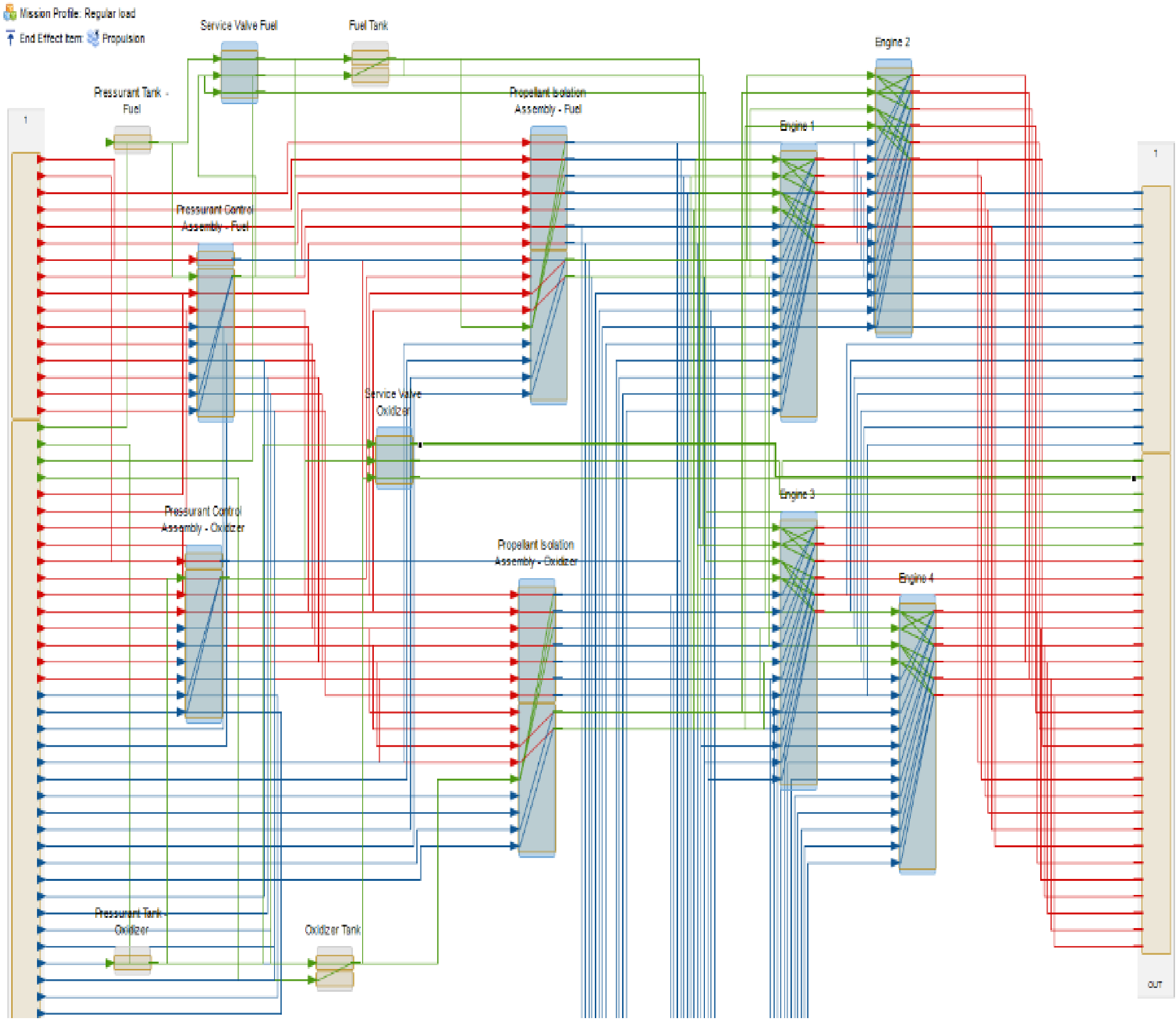


Figure 4: MADe model of the Spacecraft propulsion system.

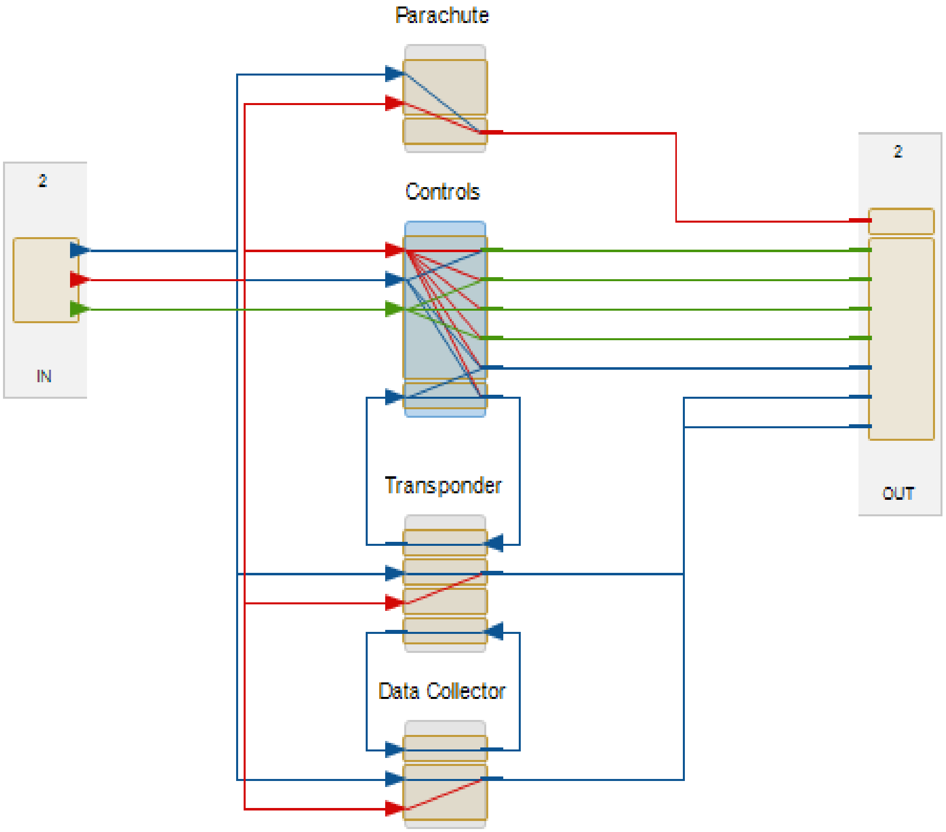
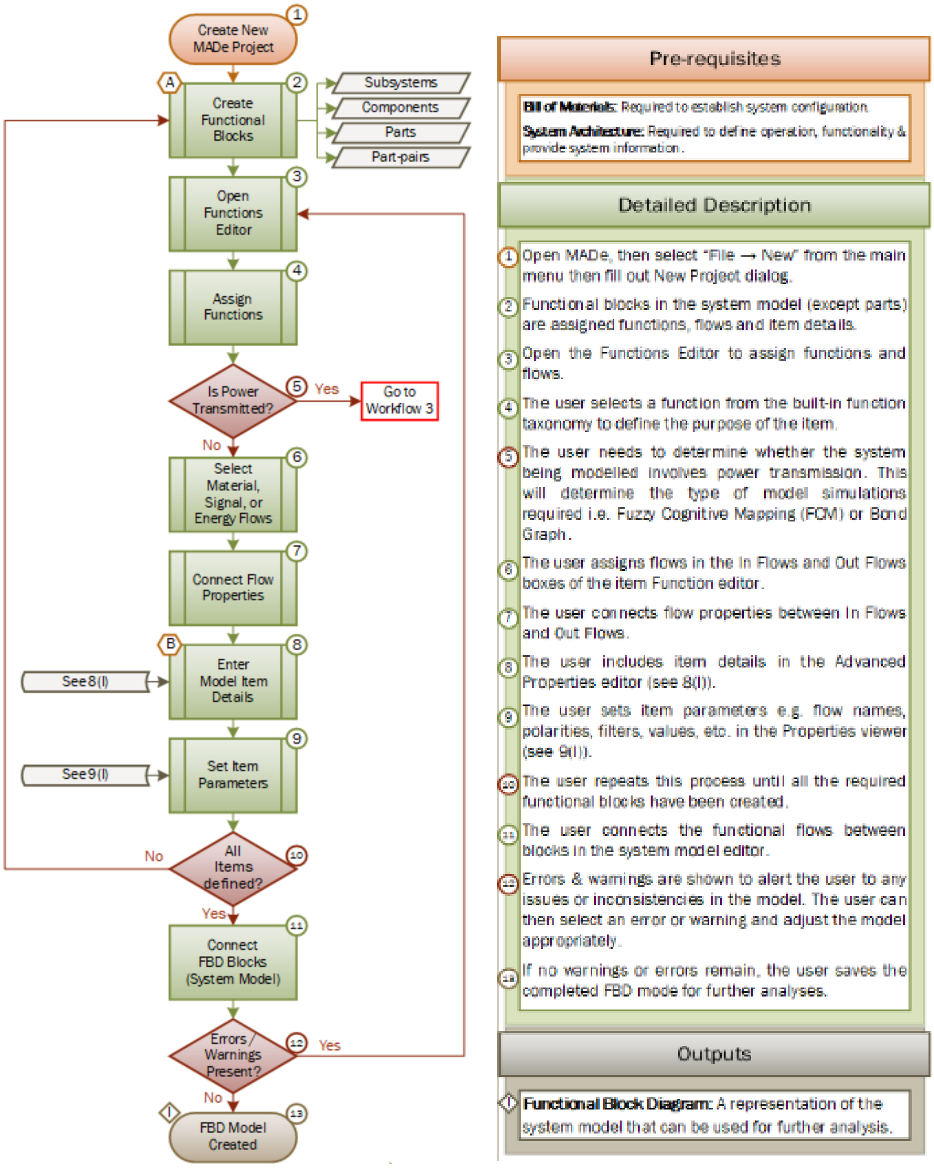


Figure 5: MADe model of the Payload sub-system of the Sounding Rocket system.

4. Useful Features

4.1 Functional Modeling

According to the MADe user manual (2017), functions were defined as the actions regarding a particular component while the flows were defined as the mandatory inputs and outputs for that same component. These flows were categorized as either energy, material, or signal that received, consumed, processed, or emitted by a component. Functional modeling can be described as the management of relationships between the input and output flows for every function and each component (MADe module user manual: Functional modeling and failure definition, 2017).



Bill of Materials: Required to establish system configuration.

System Architecture: Required to define operation, functionality & provide system information.

① Open MADe, then select "File → New" from the main menu then fill out New Project dialog.

② Functional blocks in the system model (except parts) are assigned functions, flows and item details.

③ Open the Functions Editor to assign functions and flows.

④ The user selects a function from the built-in function taxonomy to define the purpose of the item.

⑤ The user needs to determine whether the system being modelled involves power transmission. This will determine the type of model simulations required i.e. Fuzzy Cognitive Mapping (FCM) or Bond Graph.

⑥ The user assigns flows in the In Flows and Out Flows boxes of the item Function editor.

⑦ The user connects flow properties between In Flows and Out Flows.

⑧ The user includes item details in the Advanced Properties editor (see 8(I)).

⑨ The user sets item parameters e.g. flow names, polarities, filters, values, etc. in the Properties viewer (see 9(I)).

⑩ The user repeats this process until all the required functional blocks have been created.

⑪ The user connects the functional flows between blocks in the system model editor.

⑫ Errors & warnings are shown to alert the user to any issues or inconsistencies in the model. The user can then select an error or warning and adjust the model appropriately.

⑬ If no warnings or errors remain, the user saves the completed FBD mode for further analyses.

Functional Block Diagram: A representation of the system model that can be used for further analysis.

Figure 6: FBD (Functional Block Diagram) modeling workflow (MADe module user manual: Functional modeling and failure definition, 2017)

The following statement must be completely understood before the user starts the functional modeling. The order of the functions at the systems level is an exact match with the order of functions in the function editor at the component level. This statement can be explained by using the components in the payload subsystem in figure 5 and the functions inside the function editor in figure 7. The blue line at the top of the transponder component is entering and exiting from both the transponder and controls components that refers to top function shown in the first tan box.

The order of events for successful function modeling in figure 6 is further explained in an example of a real spacecraft application, the transponder component which is created by the functions editor shown below in figure 7. First, the action word transmit is assigned to the first function. Next, the input flow and output flow is determined as the energy known as data. Thirdly, the correct flow property, continuous data instead of discrete data, is chosen for the input and output flows. The previous three steps are continuously repeated until all of the functions for the transponder are accounted for. Lastly, the relationships between the input and output flows for all of the functions are decided by the placement of a polarized line.

Due to the contrasting colors, easy navigation, smooth interchangeability for functions and flows, and simple layout, this feature greatly helped the user to easily read, interpret, and edit the information. Being able to edit and adjust the relationships between flows for every function directly led to the next feature, failure diagrams.

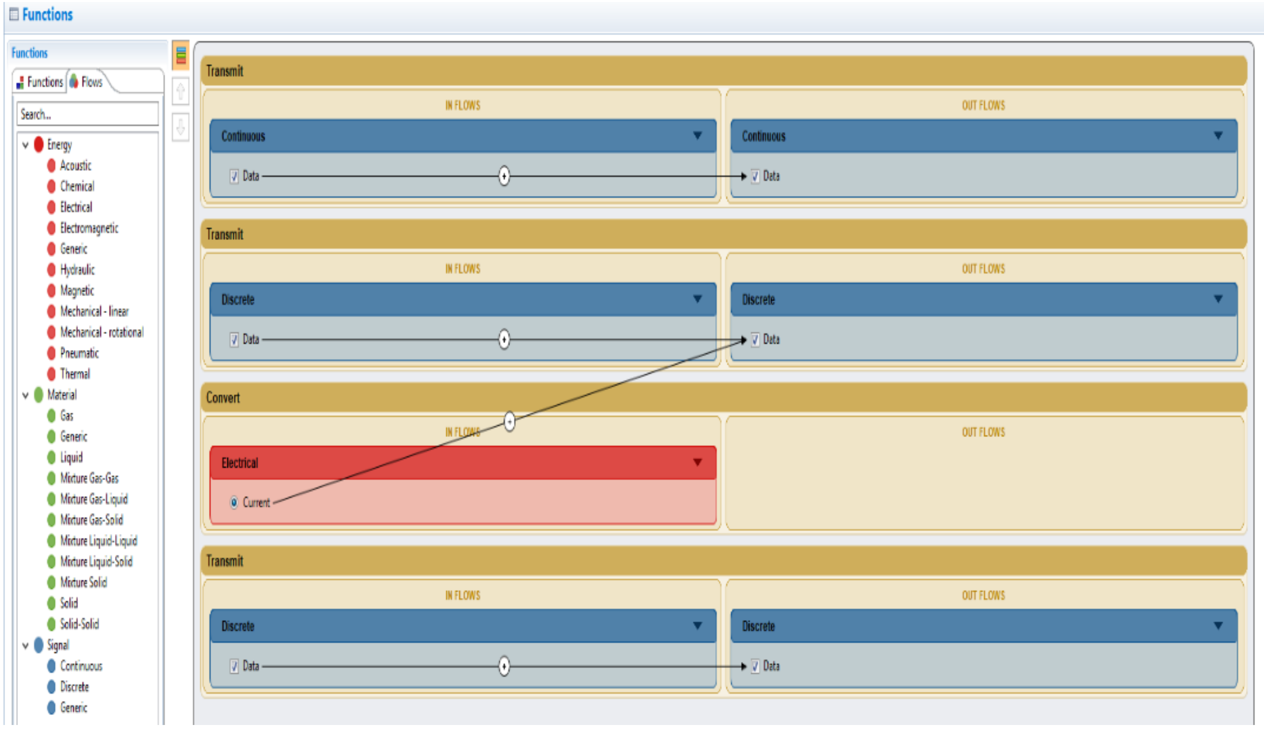


Figure 7: Functional Modeling for Transponder Component.

4.2 Failure Diagram

After the functional modeling, the team moved to generating failure diagrams. A failure diagram is a sequence of events that leads to a component's failure mode, the output flow (MADe module user manual: Functional modeling and failure definition, 2017). This MADe modeling tool feature was useful because a vast library of causes, mechanisms, and faults was provided to the user which led to a much smaller chance of leaving out a cause or fault due to human error. The efficiency of this portion of the research was increased as well due to the modeling tool's storage of several combinations of the mechanisms, faults, and causes and the ability to add or delete parts of the failure diagram almost at will. To read the failure diagram shown in figure 8, the user may start from the cause level and descend to the failure mode or vice versa.

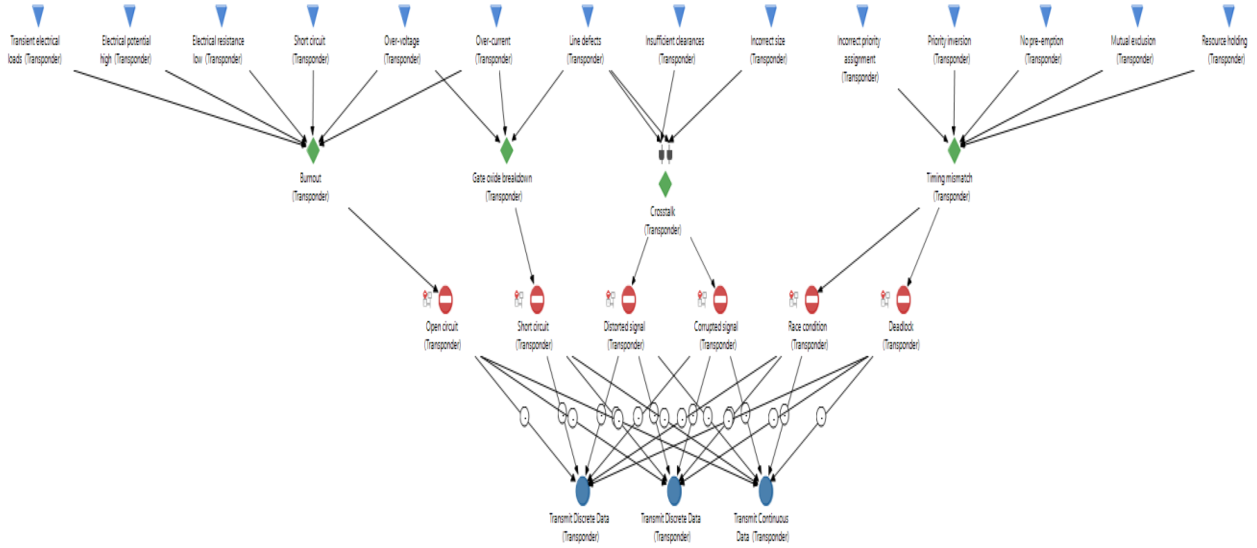
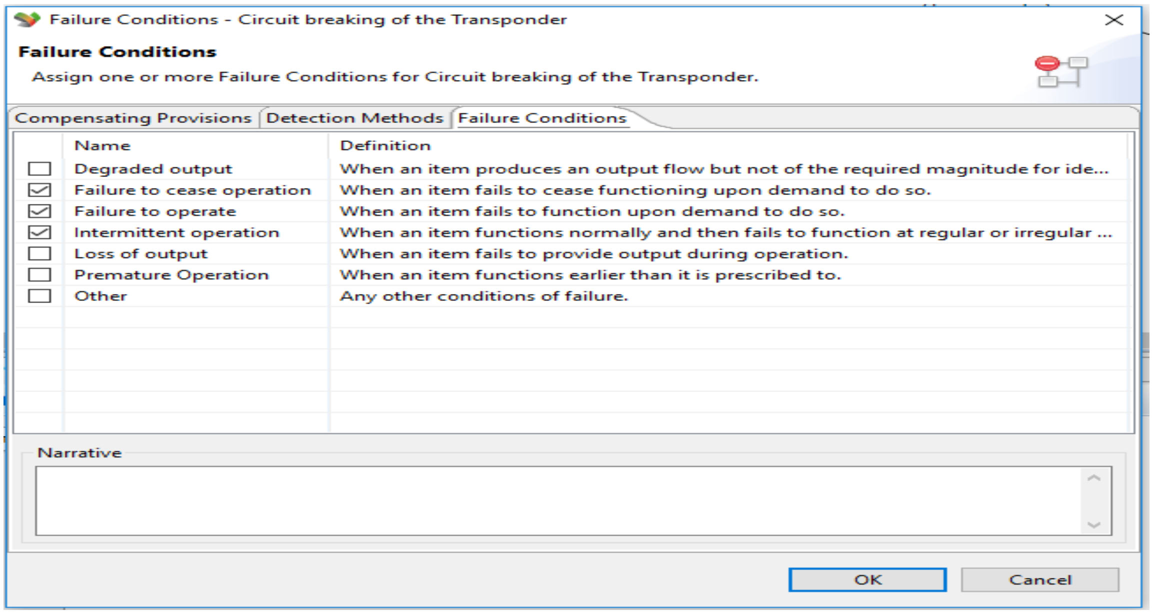


Figure 8: Failure Diagram for Transponder Component.

In figure 9, there are three significant “sub-features” of failure diagrams in the MADe modeling tool. These extra pieces of information are important because the fault in question can be described at a deeper level. Thus, the reports of the reliability analyses can increase in value. The first sub-feature is compensating provisions which addresses the question of what the component should do when a particular failure occurs such as aborting the mission, modifying the mission, or modifying the sensor. The second sub-feature is detection methods which addresses the question of when should the component be checked for preventative maintenance such as inspection or repair. The last sub-feature is failure conditions which addresses the question of what is the result of the output when the failure occurs such as failure to operate or loss of output.



Failure Conditions - Circuit breaking of the Transponder

Failure Conditions

Assign one or more Failure Conditions for Circuit breaking of the Transponder.

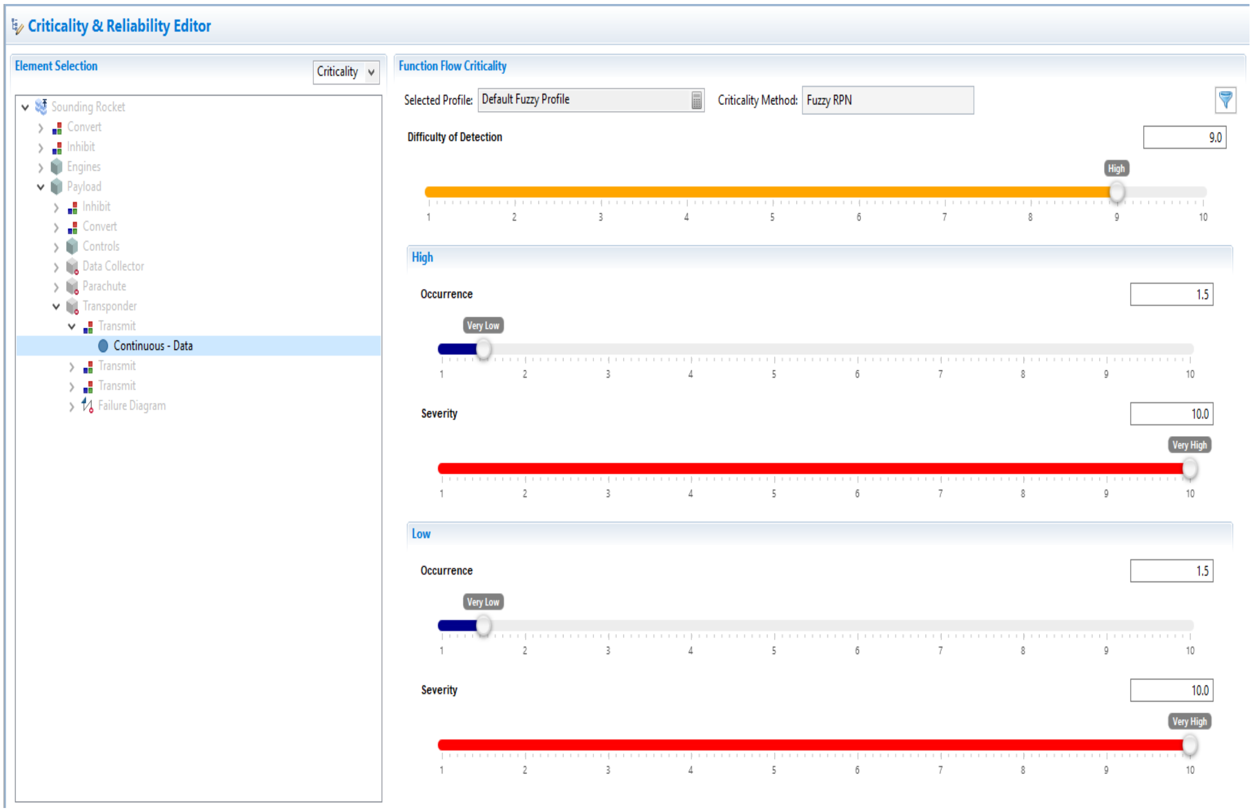
	Name	Definition
☐	Degraded output	When an item produces an output flow but not of the required magnitude for ide...
☑	Failure to cease operation	When an item fails to cease functioning upon demand to do so.
☑	Failure to operate	When an item fails to function upon demand to do so.
☑	Intermittent operation	When an item functions normally and then fails to function at regular or irregular ...
☐	Loss of output	When an item fails to provide output during operation.
☐	Premature Operation	When an item functions earlier than it is prescribed to.
☐	Other	Any other conditions of failure.

Narrative

Figure 9: Sub-features of failure diagrams for the Transponder.

4.3 Difficulty of Detection, Occurrence, Severity

In order to accurately calculate the reliability of a system as a whole, the team needed to set the failure rates to each component with the Criticality & Reliability Editor. The MADe modeling tool used three sub-features of criticality to determine the failure rates that are shown in figure 10.



Selected Profile: Default Fuzzy Profile

Criticality Method: Fuzzy RPN

Difficulty of Detection: 9.0 (High)

High

Occurrence: 1.5 (Very Low)

Severity: 10.0 (Very High)

Low

Occurrence: 1.5 (Very Low)

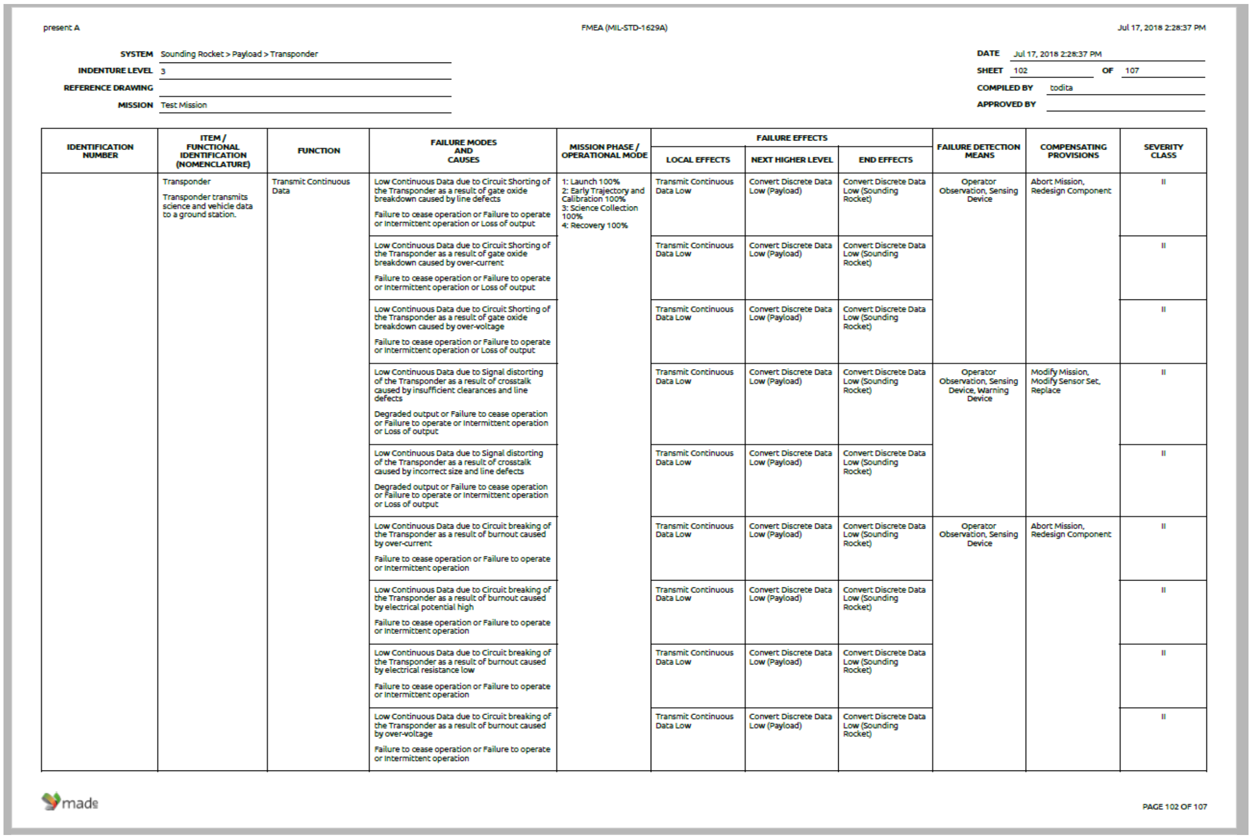
Severity: 10.0 (Very High)

Figure 10: Sub-features of criticality for the Transponder.

The first sub-feature is difficulty of detection which answers the question of how hard it is to identify a specific failure. The second sub-feature is occurrence which answers the question of how frequently does a certain failure occur. The final sub-feature is severity which answers the question of how bad would the failure affect the entire system.

5. Reliability Analyses

After the models were created and all of the features were applied, the team generated the reliability analyses in report form. The first major analyses were the Failure Mode Effects Analysis (FMEA), shown in figure 11, and the Failure Mode Effects & Criticality Analysis (FMECA). Both of these reliability analyses lists the failure mode for each component in the model that leads to an end effect/outcome and uses several features such as functional modeling, failure diagrams, and severity. The FMECA has several additional features that focuses on the Criticality aspect such as occurrence and detection.



present A

FMEA (MIL-STD-1629A)

Jul 17, 2018 2:28:37 PM

SYSTEM Sounding Rocket > Payload > Transponder
INDENTURE LEVEL 3
REFERENCE DRAWING
MISSION Test Mission

DATE Jul 17, 2018 2:28:37 PM
SHEET 102 **OF** 107
COMPILED BY todita
APPROVED BY

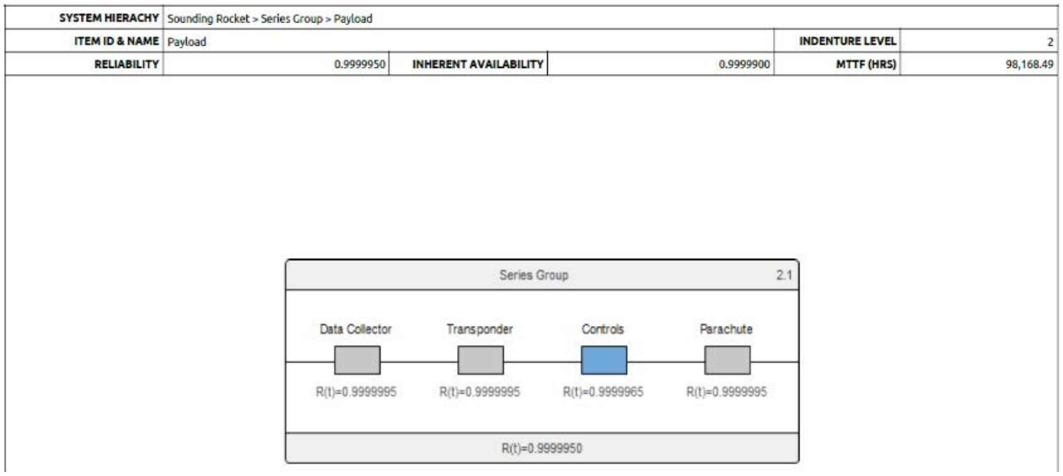
IDENTIFICATION NUMBER	ITEM / FUNCTIONAL IDENTIFICATION (NOMENCLATURE)	FUNCTION	FAILURE MODES AND CAUSES	MISSION PHASE / OPERATIONAL MODE	FAILURE EFFECTS			FAILURE DETECTION MEANS	COMPENSATING PROVISIONS	SEVERITY CLASS
					LOCAL EFFECTS	NEXT HIGHER LEVEL	END EFFECTS			
	Transponder Transponder transmits science and vehicle data to a ground station.	Transmit Continuous Data	Low Continuous Data due to Circuit Shorting of the Transponder as a result of gate oxide breakdown caused by line defects Failure to cease operation or Failure to operate or Intermittent operation or Loss of output	1: Launch 100% 2: Early Trajectory and Calibration 100% 3: Science Collection 100% 4: Recovery 100%	Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)	Operator Observation, Sensing Device	Abort Mission, Redesign Component	II
			Low Continuous Data due to Circuit Shorting of the Transponder as a result of gate oxide breakdown caused by over-current Failure to cease operation or Failure to operate or Intermittent operation or Loss of output		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)			II
			Low Continuous Data due to Circuit Shorting of the Transponder as a result of gate oxide breakdown caused by over-voltage Failure to cease operation or Failure to operate or Intermittent operation or Loss of output		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)			II
			Low Continuous Data due to Signal distorting of the Transponder as a result of crosstalk caused by insufficient clearances and line defects Degraded output or Failure to cease operation or Failure to operate or Intermittent operation or Loss of output		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)	Operator Observation, Sensing Device, Warning Device	Modify Mission, Modify Sensor Set, Replace	II
			Low Continuous Data due to Signal distorting of the Transponder as a result of crosstalk caused by incorrect size and line defects Degraded output or Failure to cease operation or Failure to operate or Intermittent operation or Loss of output		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)			II
			Low Continuous Data due to Circuit breaking of the Transponder as a result of burnout caused by over-current Failure to cease operation or Failure to operate or Intermittent operation		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)	Operator Observation, Sensing Device	Abort Mission, Redesign Component	II
			Low Continuous Data due to Circuit breaking of the Transponder as a result of burnout caused by electrical potential high Failure to cease operation or Failure to operate or Intermittent operation		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)			II
			Low Continuous Data due to Circuit breaking of the Transponder as a result of burnout caused by electrical resistance low Failure to cease operation or Failure to operate or Intermittent operation		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)			II
			Low Continuous Data due to Circuit breaking of the Transponder as a result of burnout caused by over-voltage Failure to cease operation or Failure to operate or Intermittent operation		Transmit Continuous Data Low	Convert Discrete Data Low (Payload)	Convert Discrete Data Low (Sounding Rocket)			II

made

PAGE 102 OF 107

Figure 11: FMEA Reliability Analysis

The second important analysis was the Reliability Block Diagram (RBD), shown in figure 12. This reliability analysis contains valuable information such as mean time to failure, availability, and most importantly, reliability.



SYSTEM HIERACHY	Sounding Rocket > Series Group > Payload				
ITEM ID & NAME	Payload			**INDENTURE LEVEL**	2
RELIABILITY	0.9999950	**INHERENT AVAILABILITY**	0.9999900	**MTTF (HRS)**	98,168.49

Figure 12: Reliability Block Diagram

The final key analysis was the Fault Tree Analysis (FTA) shown in figure 13. This reliability analysis was the complement of the RBD which means that the focus was on calculating the percent chance of failure per component. This analysis was also an excellent visual aid that represented the decomposition of faults from the highest system level to the lowest component level.

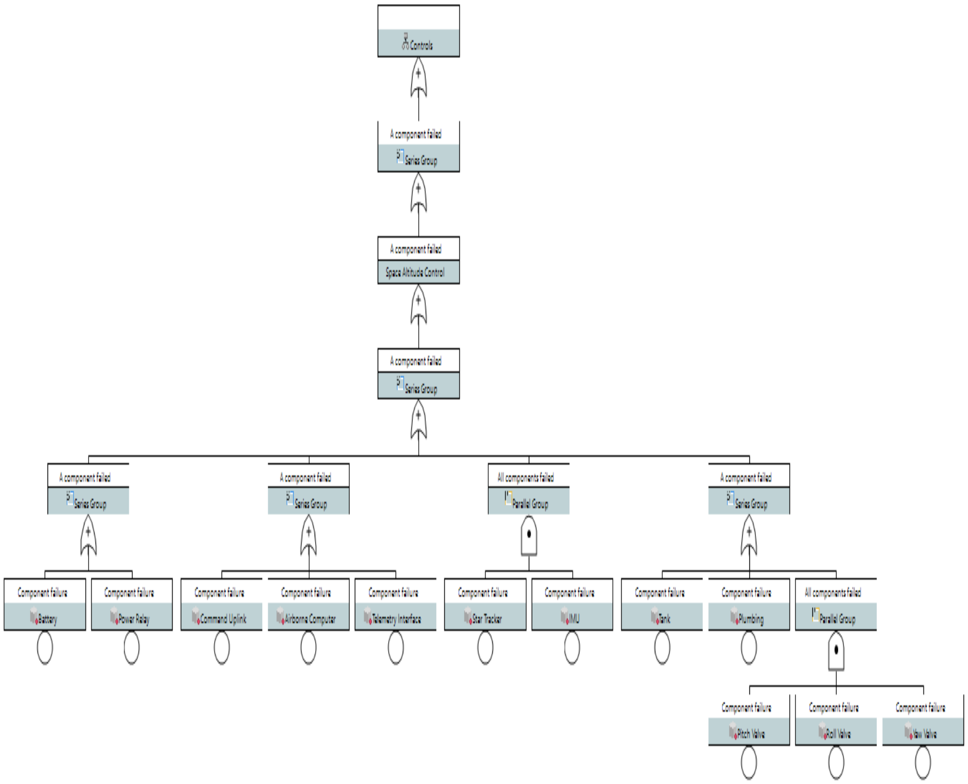


Figure 13: Fault Tree Analysis

6. Concluding Remarks

There were several challenging, but rewarding moments during this study. Due to the immense volume of buttons and windows, a majority of the student's time was spent in learning how to navigate within the tool itself. The modeling tool is not as intuitive as we wish, with most features only operating with specific commands. There was a massive amount of errors and warnings that in some cases affect each other. Even though these challenges were frustrating, the MSU team felt quite accomplished when the correct process and procedure was determined. The team learned that the standards of the customer were supremely important. Even though MADe had many benefits, there were some additional adjustments that must be made in order to satisfy the users such as adding more customized failure modes and renaming several columns in the FMEA. In conclusion, the MADe modeling tool has a tremendously high potential for future aerospace projects.

Acknowledgements

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