Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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# Using Model Based Systems Engineering to Improve Design Decisions and Communications in Student CubeSat Projects

Master's thesis in Mechanical Engineering
Supervisor: Cecilia Haskins
Co-supervisor: Evelyn Honoré-Livermore
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## Abstract

NTNU Small Satellite Lab is supporting the Hyper Spectral Imager for Oceanographic Applications mission. The goal of the mission is to launch a CubeSat satellite to support oceanographic applications. As part of the mission, the use of Model Based Systems Engineering is investigated to find how it can support design development and improve design decisions and communications in the project. The Open-Source software Capella will be used to implement a model of pre-existing code to demonstrate the possibilities of reverse engineering existing project data. A literature study is performed to investigate the research on Model Based Systems Engineering, and it will be used to investigate the effect it has on trans-disciplinary communications. Finally, a suitable software will be chosen for use in coming Hyper Spectral Imager for Oceanographic Applications missions using a trade-off study and the Analytic Hierarchy Process.

## Sammendrag

NTNU Small Satellite Lab jobber på Hyper Spectral Imager for Oceanographic Applications-oppdraget. Oppdragets mål er å sende opp en CubeSat-satellitt for å bidra til oseanografiske oppdrag. Som del av oppdraget har bruken av modellbasert systemingeniørvitenskap blitt undersøkt for å finne ut hvorvidt det kan bidra designutvikling og i å forbedre avgjørelser knyttet til design og kommunikasjon i prosjektet. Open-Source-programvaren Capella brukes til å implementere en modell av eksisterende kode for å demonstrere mulighetene til å jobbe seg bakover fra eksisterende prosjekt-data for å implementere en modell. Et litteraturstudium gjennomføres for å undersøke forskning på modellbasert systemingeniørvitenskap, og det vil bli brukt til å undersøke påvirkningen det har på kommunikasjon på tvers av fag. Til slutt vil en passende programvare bli valgt for bruk i kommende Hyper Spectral Imager for Oceanographic Applications-oppdrag, ved hjelp av en handelsstudie og den analytiske hierarki-metoden.

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I also wish to thank everyone working on the Hyper Spectral Imager for Oceanographic Applications project who helped me with feedback, helped in gathering relevant data for the thesis and in being available for interviews to get a better understanding of the project and my own work.

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# Nomenclature

| | |
|---|---|
| **ADCS** | Attitude Determination Control System |
| **AHP** | Analytic Hierarchy Process |
| **AMOS** | NTNU AMOS - Centre for Autonomous Marine Operations and Systems |
| **FPGA** | Field-programmable Gate Array |
| **GPIO** | General-purpose Input/output |
| **HSI** | HyperSpectral Imager |
| **HYPSO** | Hyper Spectral Imager for Oceanographic Applications |
| **MBSE** | Model Based Systems Engineering |
| **OPU** | On-board Processing Unit |
| **RFLP** | Requirements, Functional, Logical and Physical Architecture |
| **SE** | Systems Engineering |
| **SysML** | Systems Modelling Language |
| **UML** | Unified Modelling Language |

# 1 Introduction

## 1.1 Background

The objective of this master's thesis is to gain an understanding of how Model Based Systems Engineering (MBSE) software can be used to organise and improve design decisions and communications in a student CubeSat project. This understanding will be gained through a literature study of the most recent research on the capabilities of MBSE and MBSE software. The knowledge of the advantages and disadvantages of MBSE software will be used to choose a specific tool suitable for use by the NTNU SmallSat Lab, specifically the Hyper Spectral Imager for Oceanographic Applications (HYPSO) mission. While researching the capabilities of MBSE software, a suitable software will be used to enable integration with one element of the system-of-interest.

MBSE is a methodology that uses domain models to manage information. Any complex engineering project requires information and data on the project Requirements, Functional, Logical and Physical architecture (RFLP) which makes up the project. This can include demands from the stakeholders in a projects that need to be met, limitations from the technology side of things, budget limitations, hierarchical information about project members, snippets of code, 3D-models, simulation results and more. MBSE software aim to reduce errors in development by removing natural language and its ambiguities. It also aims to keep all project members up to date on recent development from other teams by keeping all information in one platform. Any project of sufficient complexity benefits from implementing MBSE. (*MATLAB and Simulink for Model-Based Systems Engineering - Design, analyze, and test system and software architectures* 2021)

NTNU SmallSat Lab is an collective which aims to gather small satellite and other space related activities under one name to improve performance and increase visibility for the different projects. They are supported by NTNU, AMOS, Norwegian Research Council, Norwegian Space Agency, ESA and others. (*NTNU Small Satellite Lab* 2021)

## 1.2 Objectives

Vendors offer MBSE software that have different advantages and disadvantages. A trade-off study will be performed to investigate which currently available software would be best suited for use in coming HYPSO projects. Through researching the capabilities of the different software and performing an in-depth literature study a thorough understanding of the possibilities of MBSE software will be acquired. This understanding will be used describe in which ways MBSE software can improve design and communications in a complex project. During research for the capabilities of different software an MBSE model will be created through reverse engineering of existing system code relevant to the HYPSO project. The objectives are presented as a list of research questions below.

R1. How adaptable are different available MBSE software for use in a student CubeSat project and which ones are best suited for use in coming HYPSO projects?

R2. How can MBSE help improve transdisciplinary communications and the design of scientific components?

R3. How can MBSE be used to implement a model for future project management through reverse engineering of existing project data?

# 2 Theoretical Foundations

The following chapter will explain the theoretical foundations for the work done in this thesis. The necessary knowledge for reading and comprehending the findings of this thesis will be outlined. For a detailed understanding of the presented theory, additional reading is required.

First is presented an overview of what Model Based Systems Engineering (MBSE) is. This chapter also presents in-depth explanations of the terms presented as part of explaining MBSE.

## 2.1 Model Based Systems Engineering

Model Based Systems Engineering (MBSE) is a systems engineering methodology of managing projects and data through creating a graphical model of a system and its elements. MBSE Software, such as Capella or Cameo, is used to manage Requirements, Functional, Logical and Physical Architecture (RFLP). RFLP covers information about what the system is required to do, how it interacts with users, which functions are required to perform its requirements, and how user interactions and functions are implemented in terms of physical parts. As described by (SEBoK 2021a), MBSE is:

> Model-based systems engineering (MBSE) is the formalised application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.

To help further understand MBSE it is relevant to define Systems Engineering (SE) itself. SE is a transdisciplinary approach and method of implementing successful systems that fulfill requirements and needs presented by stakeholders, customers and users of the systems(SEBoK 2021b). A system is a collection of components which work together as a whole to give a solution to a problem. The components can be hardware, software and human and the system defines how these should co-operate in an organised way to achieve a goal defined through requirements(Dick et al. 2017, p. 5).

While a simple project that is small in scale might not need a formal SE approach, complex projects benefit greatly from applying SE tools (*Systems Engineering - What Is Systems Engineering?* 2021). Managing requirements across disciplines increases in difficulty as projects become more complex and SE software simplifies this process while allowing access to critical data to project members. MBSE uses models to simplify the exchange of information between projects members further.

Projects that are sufficiently complex require MBSE to keep up with change in requirements and to efficiently exchange data between project groups. MBSE software allows for communication between it and other engineering software. This means any results from simulation and analysis in another program may be imported into the MBSE software. With sufficiently complex systems the MBSE software could automatically import information from other programs to update new requirements and data.

One of the key aspects of MBSE software is to remove the need for the typical document orientation of a project (Spangelo et al. 2012). Text stored in several documents is a poor way of keeping a complete overview of a project. MBSE does away with this and creates visual diagrams that convey information more easily and accurately. Through elements such as functions, functional exchange between functions, actors, and components the MBSE software is able to visually represent the RFLP architectures in an easy-to-understand fashion. Using the build in capabilities we are able to keep track of which actors and elements interact with each other and directly on the system and we can define which interactions are expected to prepare the engineers further down the line for the challenges they will need to solve.

Any project created in MBSE software follows the same general step by step progress towards a complete architectural overview of a system. It starts by gathering the requirements and creating operational architecture. The requirements are largely driven by the needs of the stakeholders in any given project, and by technological limitations as well as the budget. The requirements are then refined into the system architecture. The system architecture defines which functions the final product needs and how actors and outside components can interact with the system. Through defining a fully fledged system before delivering the project details to the specialised engineers further down the line, the engineers know from the outset which capabilities are necessary for the system to deliver on its requirements. This also increases the safety of the final product, as special attention should be given to risks involved with use of the product.

After the system architecture is in place it is time for the logical architecture. The role of the logical architecture is to define how system functions will be realized. It provides rules on how system functions are allowed to interact with elements and actors. It also creates environments for the different parts of the system, which can be divided into subsystems. This provides an easy overview of different system elements that are reliant on the same inputs and outputs and interact with the system in similar fashion. (*MATLAB and Simulink for Model-Based Systems Engineering - Design, analyze, and test system and software architectures* 2021) (Arikan and Jackson 2019)

The following sections takes a closer look at RFLP and what the individual terms represent.

## 2.2 Requirements

There are different types of requirements relevant to systems engineering. The two main types are system requirements and stakeholder requirements. System requirements are the requirements that describe which functions are required to fulfill the objectives of the system. These system requirements are defined by the needs and requirements of the stakeholders in a project. At the beginning of a project stakeholders must meet with the system engineers and the team performing the project on behalf of the stakeholders. At this point stakeholders should define their needs and requirements to the system as rigorously as possible for the system engineers to break them down into smaller elements. Different elements of the needs and requirements are relevant to different teams of engineers and the system engineer will define the elements so that engineers of other disciplines need only relate to the elements that are relevant to them.

Stakeholder requirements are often described in statements of natural language which lack precision. It is part of the system engineers' job to translate these statements into engineering-oriented language that should be unambiguous. The needs and requirements of the stakeholders define what the system must be able to do and the system engineer must translate these requirements into precise language and functions that the system needs to fulfill stakeholder expectations. The role and definitions of requirements in systems engineering are described by the Systems Engineering Body of Knowledge at (SEBoK 2021e).

## 2.3 Functional Architecture

In relation to SE, architecture can be described as the decomposition of a system into the elements that make up the system, more specifically, the functional components and the exchange between these components (Böhmann 2014, p. 2). The functional architecture, or structure, is a collection of functions that the system must be able to perform to fulfill requirements. As described by (Blanchard and Fabrycky 2011, p. 100), "A function refers to a specific or discrete action (or series of actions) that is necessary to achieve a given objective (...)." The functional architecture also describes how functions interact with each other and how the interactions affect the outcome. Functional architecture can only be created once requirements are defined so that the necessary functions of the system can be described. Functional architecture aims only to describe what needs to be achieved by the system, not how to achieve it. The process of creating the functional architecture is one of decomposition, where needs and requirements are broken down into actions and these actions broken down into its smallest constituents. In MBSE this decomposition is represented by functional flows where you can trace any decomposed function back to its original action created by the requirements (*OMG Systems Modeling Language (OMG SysML™)Tutorial* 2009).

## 2.4 Logical Architecture

The logical architecture is typically implemented after the functional architecture. The logical architecture is the exploration of the necessary logical components in terms of logical functions and the interactions between them. It does not begin to consider the technological implementation of the required functions, as this is reserved for the physical architecture (Roques 2018, p. 177-182). Logical architecture is the in-between from functional to physical architecture in the sense that it refines the needs and requirements to concrete functions and actions that the system must be able to perform. It creates an environment during development where requirements can be refined into actions that answer to the needs of stakeholders and users without the limitations of previous visions of implementation or technology. It can be used to describe the logical functionality of both hardware and software, and can describe them in different levels of detail dependant on the component being described. Typical diagrams related to logical architecture include logical architecture breakdown, which describes the functions related to one part of the logical system with its relevant components, and exchange scenarios, which describe a timeline for the order of execution of functions that work together to complete a task. Using these diagrams, it is possible to identify the flow of information in and out of the system and operational scenarios which describe how the system operates in different use cases (SEBoK 2021c). As part of the thesis' third research question a logical architecture is presented in chapter 4.2 and shows the use of logical architecture breakdowns.

## 2.5 Physical Architecture

The physical architecture describes the hardware in terms of chosen technology to solve the functional requirements of the system. It is the layout of the physical components and how every component relates to each other. The architecture contains both ideas and visualisations of solutions to incorporating the functions from the logical architecture, and specific technology that can perform the same functions. It is important in developing the physical architecture that the logical architecture describes functions that answer to the requirements and needs of the stakeholders for the physical implementation to fully achieve the goals of the system. Physical architecture also requires a set of solutions on how to maintain the system and to decide on the longevity of the system. These could be requirements introduced by the engineers, which would be different from stakeholder requirements. Another example of engineering requirements are the physical interfaces. The interfaces would simplify the interaction of the system with other systems. Typical examples are ISO standards of nuts and bolts, and input/output ports of computers. Physical interfaces are also part of the system itself, and is what allows the physical elements of the system to interact.

The goal of the physical architecture model is to create a foundation which aids in developing the best physical implementation of the system, answering to the stakeholder requirements. The development of the model produces several options of implementation and helps facilitate a study on which implementation best suits the requirements of the system. Such a study would typically compare different implementations and score them on criteria such as cost, weight, size, number of components and interfaces and compatible technology (SEBoK 2021d).

## 2.6 The Importance of the Systems Modelling Language

The Systems Modelling Language (SysML) is a general-purpose graphical modelling language, build specifically to support SE (Casse 2017, p. 1-3). SysML is based upon the Unified Modelling Language (UML), specifically UML 2, which is a standardised modelling language consisting of a set of diagrams made to support visualisation and documentation during software or system development (Gu et al. 2012, p. 1-2). SysML borrows some of the diagrams from UML and introduces some of its own. Of particular interest to this thesis is the replacement of UML's Class diagram with SysML's Block diagram, and the introduction of the Requirements diagram. The Block diagram is a way of collecting information that describes a system or component into one block. The Requirements diagram allows the user to capture functional, performance, and interface requirements (*MBSE and SysML* 2021).

SysML is developed to make the modelling language accessible to more users, and it provides the necessary tools to model for different SE problems. In terms of MBSE, SysML proposes that the models can be presented from different perspectives, making information available to relevant users, while hiding irrelevant information. SysML is specified by an International Standard which is kept up to date by the Object management Group. The current version of the language is 1.6 and SysML version 2.0 is expected to release soon after the completion of this thesis. By adhering to the SysML standard, MBSE software ensures that models can be imported and exported to and from other software. This allows for models to be reviewed in software besides the one the model was originally created in. It is important that the software keep up to date with the latest versions of SysML for this cross-platform functionality to work.

SysML has several advantages when used for MBSE. UML lacks some of the capabilities of SysML, as UML tends to be software centric. SysML is more flexible when used for system development. It has Requirement diagrams and Parametric diagrams, which are not available in UML. The Parametric diagrams can be used for performance and qualitative analysis which allows the user to compare solutions from the physical architecture.

## 2.7 CubeSats

As defined by (Crusan and Galica 2017, p. 51): “CubeSats are small research spacecraft called nanosatellites, built to standard dimensions of 10×10×10cm units or U.” They typically weight less than 3lbs per U. CubeSats are a way for educational institutions and non-profit organisations to access space in a low-cost manner. CubeSats are typically launches together with planned satellite missions, which increases the benefits of the launch and decreases costs tied to launching the CubeSat. NASA provides the CubeSat Launch Initiative which offers access to space for small satellites, CubeSats, for smaller actors to be able to perform research in space without needing to launch their own rockets. Launching a CubeSat containing the Hyperspectral Imager is the goal of the HYPSO-1 mission. The CubeSat will allow for hyperspectral imaging that will enable ocean colour remote sensing and oceanography. By launching the equipment as a CubeSat, it will allow for low-cost implementation of the technology, which will demonstrate the capabilities and limitations of the technology.

## 2.8 Communications in Project Teams

CubeSat projects are typically transdisciplinary projects that require collaboration in multidisciplinary teams. This type of collaboration is called co-design, defined by (M. S. Kleinsmann 2006, p. 30) as:

> Co-design is the process in which actors from different disciplines share their knowledge about both the design process and the design content.They do that to create shared understanding on both aspects, to be able to integrate and explore their knowledge and to achieve the larger common objective: the new product to be designed.

The process of co-design is further investigated in (M. Kleinsmann and Valkenburg 2008), where they make the point that actors in a project must create and integrate knowledge to design a product. Knowledge in any given project is typically shared orally or through textual documents, and at times drawings and prototypes play an essential part in conveying knowledge. The process of conveying information and knowledge between members of a team is often difficult and the method chosen for doing so often influences the quality of the design communication. It is often difficult because members have different backgrounds and interests when it comes to their project and their responsibility to the design.

With this is mind, this thesis investigates the possibilities presented by MBSE software to improve the sharing and integration of knowledge between team members. It is relevant to investigate which tools can be used to share information, how this information is shared between team members, how this information is presented to team members and if these tools can replace other often used methods of sharing knowledge.

## 2.9 Trade-Off Studies

A trade-off study is a decision analysis methodology for finding suitable alternatives to a given objective (Garber et al. 2015). Any trade-off study consists of an objective which can be solved in different ways, a set of relevant alternatives that differ in a relevant way, a set of criteria based on mission objectives and requirements on which to rate the alternatives, and information and uncertainties about the performance of each of the alternatives (Buede 2014).

In order to select a suitable MBSE software for use in coming HYPSO projects, a trade-off study is performed. This will compare different available software to each other and looks for advantages and disadvantages of each software. This trade-off study is conducted according to the procedure described in chapter 3.2. The chapter shows how any trade-off study is reliant on defining the objective to develop criteria that can be used to find suitable candidates. These objectives must be created from the needs of the project they are intended for.

# 3 Methods and Tools

## 3.1 Interviews

As part of choosing a suitable MBSE tool for HYPSO-project planning interviews were performed with team leaders. The HYPSO team consists of six team leaders reporting to the project manager. The teams at the time of performing the interviews were System Integration and Electronics, HyperSpectral Imager (HSI) Payload Hardware, Attitude Determination  Control System (ADCS), On-board Processing Algorithm, Mission and Operations. When choosing a suitable MBSE tool, the requirements from the stakeholders in a project are essential to choosing the correct tool. The stakeholders in HYPSO are in this thesis considered the project manager and the team leaders. The typical role of the stakeholders is to detail a goal for the project, certain requirements the project must fulfill and milestones to achieve along the way. In interviewing the team leaders a better understanding of goals and requirements will be achieved.

Interviews were performed over an online communication platform with voice and camera. Face to face interaction were not possible due to Covid-19 restrictions.

The method of interviewing used for the purpose of gathering information about the teams needs and their working methods was the qualitative interview. As outlined by Robert K. Yin in (Yin 2011, p. 132-142) the interview can be performed in one of two ways, either the structured or the qualitative interview. The qualitative interview has certain benefits that made it preferable for gathering information in this project. The qualitative interview allows for a more social form of interviewing which leads to more natural answers. This allows the interviewee to give open-ended answers which can elaborate beyond the scope of the original question. By listening and fully understanding the answers provided, it is possible to further build upon the answers and gain new insight by asking follow-up question based on the given answers.

The team leaders were given the questions ahead of the interviews to prepare their answers. The list of questions follows below:

Q1. What are the goals and responsibilities of your team?

- (a) What is the goal – the main objective for your team?
- (b) What responsibilities does your team have to the project and the other teams?

Q2. What software/programs does your team use?

Q3. How does the team members store their data and their work?

Q4. How does the team members share their data with other teams and what team need access to data from your team?

The notes taken from the interviews are presented in appendix A and the findings are presented in chapter 4.1.

## 3.2 Trade-Off Study

This section presents the basic principles of a trade-off study according to (Kossiakoff et al. 2011, pp. 282-295). A simple overview of the basic principles and the order in which they should be explored are presented in figure 1. It is essential to any trade-off study to start by defining the objective of the study. This is defined by the mission goal, the requirements to the solution and the interest of the stakeholders. The objectives need to be measurable to rate how well an alternative meets with the objective. This allows alternatives to be compared to each other, which makes it possible to choose the best suited alternative.

Once the objective has been defined, it will be used to produce a set of criteria. These criteria will be directly measurable in order to compare the alternatives on their ability to meet the criteria.

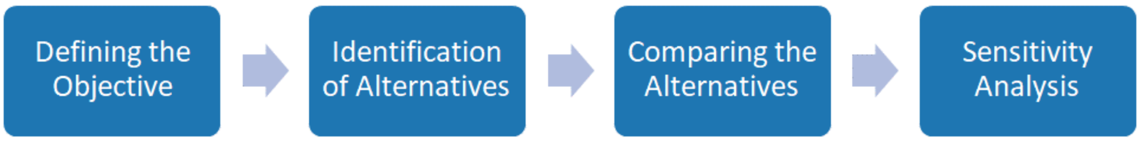


Figure 1: A overview of the basic principles of a trade-off study according to (Kossiakoff et al. 2011)

Criteria should be rated on a scale from 0-100 and the scores should reflect how well each alternative performs compared to the other alternatives. This means the set of scores cannot be compared to alternatives outside the scope of the study, as the scores only compare alternatives to each other.

With the criteria defined it is time to explore alternatives. In this paper the focus of the trade-off study is to identify a suitable MBSE software for use in coming HYPSO projects. This work benefits from comparing a large set of software. The methods used to compare the software depends on the requirements of the software. The requirements will be part of the foundation for creating the objective of the study.

After generating a set of alternatives, they will be compared to each other. In addition to evaluating the alternatives on their ability to meet requirements, the different criteria will be weighted differently based on their importance to requirements and stakeholder needs. How the criteria is weighted and why they are weighted as they are will be presented as the criteria is presented in chapter 4.3.4.

Once the alternatives have been evaluated, a sensitivity analysis should be performed. This is to validate the findings and verify that scores appropriately reflect the effectiveness of the different alternatives. As part of validating the trade-off study it is a constant loop of checking for and potentially discovering new alternatives. It is assumed at the outset of the trade-off study that information about individual alternatives and the set of alternatives is not complete. As stated in (Buede 2014, p. 8):

> The pitfalls of trade studies include missing important alternatives or objectives, and being overconfident about the future, especially the system's context, its usage, the various technologies to be employed in the system, or the architecture's capabilities.

In order to compare the alternatives in the trade-off study the method of Analytic Hierarchy Process (AHP) has been used. This method is used to quantify our findings in mathematical terms. It helps in ranking the different candidates against each other based on importance to stakeholders and how well each candidate meets the criteria. AHP is described as a multi-criteria decision making method that helps in making decisions on subjective matters when multiple interests are at conflict. AHP incorporates elements of psychology and mathematics to reach a conclusion that best serves the different interests of stakeholders. It does this through pairwise comparisons. Each criterion is compared two at a time to make the decision easier on the stakeholders. After having the stakeholders compare the criteria and ranking them in terms of importance, a weighted average is calculated. Linear algebra is used to assess the results and calculate the weighted average. This presents the user with a number on how important each criterion is to the overall decision. The final step in performing the AHP method is to calculate the utility of each candidate. Utility is a measure of how well any given candidate performs on any criterion, in other words, how useful each candidate is in terms of a criterion. The work with AHP has been done according to the work presented in (Goepel 2013) and the explanation of the methodology has been supported by the work of (Ishizaka and Labib 2011).

In order to use AHP as part of the trade-off study, stakeholders were asked to fill out an excel spreadsheet where the criteria are rated against each other. An explanation on how to use the spreadsheet in Norwegian is in appendix C. The stakeholders are asked to evaluate the importance of each criterion against one other criterion at a time. In addition, the preference for either criterion is weighted with a grade from 1-9, 1 being equal importance and 9 being much more important. The spreadsheet helps keep the grading consistent and will suggest alterations to the grades and preferences if it detects large discrepancies in the given answers.

The work on the trade-off study is presented in chapter 4.3.

## 3.3 Creating a Model Using MBSE

This thesis intends to present a model created to represent existing project data. Specifically, it intends to present the logical architecture of a part of the software code that has already been written for the HYPSO project. Work started early with involving the team leader for System Integration and Electronics of HYPSO to decide upon a part of the existing code that could be implemented. The code that was chosen for modelling was the Bootloader. This part of the code was chosen as it was not too complex and would be suitable as a test in implementing code as logical architecture. The purpose of implementing a part of the existing code as a model was to gain understanding for the methodology of modelling in MBSE software and to prove a function of MBSE that can be implemented and used by team members. It was necessary to spend time learning how to use MBSE software and how to model to better understand the possibilities, the methodology and the timeframe of MBSE.

The work on creating the model started by choosing a suitable software for modelling. The most critical criterion in choosing a software to start with was usability, that it should be simple and quick to learn. It was suggested by the thesis' co-supervisor to start by using Capella. Capella is an Open Source MBSE tool that is built on the Arcadia method, which is the modelling language the software uses. The Arcadia method aims to simplify some of the rigorous implementation of SysML to make it more available to users. It supports most of the diagrams present in SysML. Capella has a tutorial, several webinars and guides available and a moderately active community. After reading up on the literature on Systems Engineering and specifically MBSE, modelling started by following the Capella tutorial.

The Capella tutorial presents a complete overview of modelling using the software. It demonstrates most diagrams related to Operational and System Analysis, as well as Logical and Physical Architecture. Following the tutorial made the concepts of modelling easier to understand. It also showed how diagrams interact with each other and easily updates information when it is changed in related views. The tutorial demonstrated how the process of modelling a system is efficient compared to other methods as the user is able to update information from several views as development of the model makes it clear what is necessary and what is not.

As work on the tutorial was finished, a meeting was held between the author, the co-supervisor, and the team leaders of On-board Processing Algorithms and System Integration and Electronics. The meeting was held to establish an understanding of the Bootloader before modelling began. The code was already fully written and implemented. It was discussed the functionality and limitations of the Bootloader, and the missing functionality that the code assumes works. The code assumes that the hardware is able to change which memory cards it checks for data, but this is not implemented in the hardware. This is described in more detail in chapter 3.3. It was stated in the meeting that the code operates on the assumption that checking the secondary memory card is possible, but that it does not prevent the code from operating even if it physically does not work. It was preferable that the part of the code that can check for data on a secondary memory storage would also be implemented in the model. With all the elements from the code in place in the model it would be possible to check for redundancy and possible simplifications to the code. This was part of the original plan for the modelling, but would have to be reserved for further work and research after the completion of this thesis.

After an understanding of the Bootloader was in place, work started on modelling in Capella. A model was created and presented to the supervisors. The first model had obvious mistakes in it and work began on making a new model that would fix these mistakes. The second model answered to the task and was approved by both the supervisors and the team leader of System Integration and Electronics. This model is presented in chapter 3.3 and a look at the model itself can be found in appendix B.

# 4 Work and Results

## 4.1 Findings from the Team Leader Interviews

The interviews conducted with the team leaders can be found in the appendix. This section will present the findings from the interviews that are the most relevant to the work of the thesis. These findings include how the teams share and integrate knowledge with each other and which software are important for interoperability in the chosen MBSE software.

All teams store their information in a mix of textual documents and spreadsheets. As the project grows it becomes increasingly more difficult to find information when it is stored in this way. Older documents might not be updated as new information is created. This creates a situation where mistakes can be made due to old information being used to perform new work. If the person in charge of a part of the project is not available and members need to find information in the growing system of textual documents and spreadsheets, mistakes have an increasing chance of happening. In CubeSat projects small errors may play a big role in whether the project is successful. One team leader stated that they were having trouble accessing information about the dimensions of a part of the CubeSat. This wastes time for the project overall and creates a situation where mistakes can be made if the wrong dimensions are used.

The teams use a few different tools in analysing, simulating, and programming for the project. The tools include Simulink, Python, GitHub, Siemens NX, ESATAN-TMS, Simulations Systems Tool Kit and others. The listed tools are the most relevant ones to integrate with potential MBSE software.

It is obvious from the interviews that the teams are connected and cooperate on a weekly, if not daily, basis. As teams generate information, it becomes increasingly important to ensure that the information is up to date and available to other project members. By sharing information in textual documents and spreadsheets, members face the challenges presented in chapter 2.8. MBSE software can be an important tool in keeping information up to date the available to appropriate project members. These findings are directly relevant to the second research question of this thesis.

## 4.2 Bootloader Model Created in Capella

This section presents the work done on modelling the Bootloader using Capella. It starts by presenting an explanation of how the Bootloader works and operates, and what its main purpose is. Then the results of the modelling are presented along with an overview of the model added in appendix B.

The Bootloader is a part of the software that aids in booting up the on-board processing unit (OPU). Just as for any computer that is booted up from a non-powered state, the OPU needs a set of instructions on what to do when first booting up. The Bootloader has code that automatically runs when the system is given power. The code is executed and tries to load the field-programmable gate array (FPGA) and to program the OS. The FPGA is an integrated circuit that is configured after manufacturing. This allows for shorter development time as the software for the circuit can be developed as the FPGA is being delivered. The OS contains all the software that executes commands and reacts to sensory inputs to the system.

In order to execute the code that makes up the Bootloader a set of memory cards are required. The implementation of the Bootloader that the HYPSO project uses requires the software to look for memory cards that should contain a bitstream and a boot image. In order to load the FPGA the code looks for the bitstream on the memory card and then looks for the boot image to initialise the OS. The implemented solution on the current system is to have a main SD card and two backup memory cards, which are the secondary SD card and the backup flash memory. As the code is executed it starts by checking the main SD card for the required bitstream and boot image and as long as both are present on the main SD card, the code will execute normally and the Bootloader will finish running. Should the bitstream and boot image not be available on the main SD card the code will start to run backup code to check the backup memory cards. The code will first check the backup flash memory for the bitstream to program the FPGA, and assumes that the data is available here. It then checks for the boot image and checks the secondary SD card if it has it available. If the boot image is not found of either the main of secondary SD card the code will run five times, executing the same code every time and increasing a counter keeping track of the number of resets. As the code reaches five resets it will start to run a different part of the code which is the backup code. This part of the code assumes the bitstream is available from the backup flash memory and loads the FPGA using this. It then checks the backup flash memory for the boot image and the code executes and finishes if it finds it there. As a final attempt at executing the Bootloader the backup code can check both the main and secondary SD cards for the boot image if it is not available in the backup flash memory. Should the code find the bitstream and boot image in any of the memory available the code will finish executing, exits the Bootloader, resets the counter keeping track of the number of resets, and runs the OS.

This code is implemented in Capella through logical architecture. The overview in appendix B shows the logical architecture breakdown of the model, showing the structure of it. It is recommended to have the overview with figures 5 and 6 available while reading the following explanation of the model. The breakdown contains the logical system, which is the Bootloader itself, which in turn contains all other elements of the model. The system contains three logical components which are the main SD card, the secondary SD card and the backup flash memory. These are included in the model to show how the code interacts with external components that need to be able to interact with the OPU. Besides the components are the functions and the functional exchanges between them. The functions describes logical actions that the system must be able to execute. Looking at the model from a perspective where no code exists yet, these functions should describe higher level actions that are necessary to execute the wanted actions for the required result. This code however starts by mimicking the existing code, and as such contains more refined functions that are more detailed than it otherwise would have been.

Two main executions of the code is highlighted in the model. The first is the one where the code executes without issue highlighted in blue. The second is where the code starts running the backup code after five resets of the code without finishing. By following either line we can see the split-function being used, directly after the function for "Bootloader checks how many resets has been performed." The split functions allows us to model a scenario where a if-statement would typically be used. A check is performed to see the state of the system, and this state determines which functions are carried out next. In this case it checks to see the count for the number of resets. By following the blue line we see how the model shows with its functions and functional exchanges how it checks for data on the main SD card and, in the case it finds what it is looking for, uses it to prepare the system for further operations. If it is successful in checking the main SD card for the boot image and bitstream, the code finishes and exits, allowing the OS to run. Should the code be unsuccessful in finding the necessary data, it will attempt to check the other memory for it. If this fails, the Bootloader resets, updates the reset counter and runs again. After five resets the backup code will execute. The Bootloader is able to keep track of the number of resets even in the case of power loss. As the Bootloader starts running, it increases the reset counter by one. The counter is stored in a flash memory which keeps its data even if it loses power. This makes sure that the Bootloader will eventually run the backup code in the case of repeated power failure and also allows for users of the system to manually power down the OPU repeatedly to force the use of the backup code for testing.

The backup code begins by assuming the bitstream exists on the backup flash memory and programs the FPGA from there. It is critical for the system to boot that the code at least exists here, otherwise the code will malfunction and nothing will be executed. The code continues to check the backup flash memory for the boot image and the code executes if it is available. Otherwise the backup code will change the state of the general-purpose input/output (GPIO) pins in order to check both the main and secondary SD cards for the boot image. The code is able to execute this command, but the current system is unable to do this on the hardware side. This results in the current system only being able to read the main SD card, as it is impossible to change between the two SD card locations. The current system therefore only has the backup flash memory as a functional backup. The code does not get interrupted by this error, as the system simply read the main SD card both times, both before and after attempting to run the code that changes positions of the GPIO pins. As the code finds the boot image on either the backup flash memory or the main SD card it finishes executing and exits the Bootloader.

The model highlights the functionality of the code and the areas that could have been improved for a new version of the OPU. It most notably highlights that the current system is unable to make use of the secondary SD card and that the code would be unable to finish if neither the main SD card or the backup flash memory contains the bitstream for the FPGA. It should never happen that the data is not available on the main SD card, but the backup exists in case of reading errors or damages to the memory of the system. By having the data available on backup memory the chance of reading the data successfully increases significantly. The next HYPSO project should aim to fix the hardware issue preventing the change of the GPIO pins in order to ensure the system operates as intended, or otherwise remove redundant code from the Bootloader. Any code that executes in order to change the state of the GPIO pins has no effect as the system currently works.

Part of the backup code reuses exact parts of the main code. This implies that the code could be further simplified for reading, making it more accessible to later changes. A separate segment of the code could be written which could be executed at the end of both the main and backup code, which is the code that changes the state of the GPIO pins and checks the other storage for the boot image. This would remove redundancy in the code.

The results and possibilities available by using MBSE software such as Capella related to the HYPSO project is discussed in chapter 5.3.

## 4.3 Trade-off Study

### 4.3.1 Presenting the Objective

This trade-off study is conducted according to the procedure described in chapter 3.2. The study starts by defining the objective. The objective is defined by the goals, needs and requirements of the project and its members.

Objective 1. Improving communications

Team member and team communication can be improved by creating an environment where information is gathered in a easily accessible way. MBSE software does away with some of the paper based flow of information and stores it graphically. Through profiles and information distribution the software gives access to relevant information while hiding irrelevant information. Distinguishing between the two can be done on a member to member basis. Software that offers integration with third-party software also allows information to automatically update as simulations and analysis is performed.

Objective 2. Improving design decisions

By offering a graphical representation of needs and requirements, MBSE software offers tools that can be used to improve design decisions. By having a systems engineer reduce design challenges into clear, precise language that focuses on the requirements of the system, design engineers are free to focus on how to solve the challenges presented. By offering requirement traceability project members can more quickly verify if their solutions meet the specifications presented by stakeholders.

Objective 3. Improving understanding

By presenting large sets of information in a easy-to-understand graphical view it is easier for members to get a complete overview of requirements and needs relevant to their work. The different architectures available in MBSE software allows for both simple and complex representations of engineering problems, allowing team members to perform analysis of problems directly in the software.

Objective 4. Improving long term achievements of the project

The models produced by MBSE software can be reused once the project moves into its next phase. For HYPSO, this means models can be produced during the work on HYPSO II and later be reused for HYPSO III. This saves on the work required to start up coming projects and improves flow of information to new members.

### 4.3.2 Creating Criteria from the Objective

The objective of the trade-off study was defined in chapter 3.2. The points presented there is used to develop the criteria in the following section. In addition, the takeaways from the team leader interviews in chapter 4.1 were considered when making the criteria.

Criteria 1. Affordability

The software chosen for the HYPSO project should preferably be free-to-use. As it is a student project costs need to be kept at a minimum. Allowing access to all HYPSO members to the chosen software is critical to improve communications and understanding. Software licenses typically increase in price with each additional license required which indicates that paid software will quickly become expensive.

Criteria 2. Integration of SysML

Integration with SysML ensures that the tool keeps up to date with the latest standards of SysML, which creates the foundation for a effective MBSE software in terms of keeping diagrams up to date and following the latest trends in adapting the tools to the users. SysML is being improved by a large community and implements many powerful diagrams for use in MBSE work. The tools based on SysML are sure to improve communications between users and the design development cycle.

Criteria 3. Plans for integration with SysML 2.0

SysML version 2.0 is set to release soon after the completion of this thesis. SysML 2.0 will incorporate the latest work on standardising the language that is the foundation for so much of MBSE work. SysML 2.0 looks to further improve the effectiveness of work using MBSE. By implementing a tool for use by HYPSO members that plan to integrate SysML 2.0, the team members are given the possibility to start using what looks to be part of the most powerful MBSE tools once it releases.

Criteria 4. Community

An active community simplifies the learning process for new users. Forums with high level of activity and user submissions is preferable. Customer support should also be available and able to help in getting users comfortable with the new software and in providing answers when the software doesn't behave as expected. This will all help in getting users situated faster and in improving models.

Criteria 5. Usability

Any member of the HYPSO project should be able to pick up and learn how to use the software, without the need for previous knowledge. It is preferable that the basics are quick to learn and that the vendor offers tutorials that simplify the learning process. Any software that provide the users with an intuitive and efficient user interface would score higher on usability. Should Community score highly for the investigated software, this would improve usability as well, as a active community can help simplify the learning process. There is also the question of how many users are necessary for efficient use of the software. It is preferable that several users can access and write to the software, while more users could open a read-only version. For the HYPSO project it is reasonable to suggest one license for each team working on the project.

Criteria 6. Interoperability

The software should preferably be able to incorporate models from similar type software and also be open to integration with other types of third-party software. This would be possible if there is a focus on being able to work with different model types and modelling languages, and if there is an readily available API which lets users create communications between programs. The software implemented by HYPSO members are mentioned in chapter 4.1 and the chosen software should preferably be able to export and import data to these programs.

### 4.3.3 Presenting the Alternatives

This section presents the work performed to find suitable candidates that fulfill the criteria of the study. Given our criteria we need potential candidates to pursue. A list of candidates is given below:

C1. Capella (Open Source) by PolarSys

C2. Modelio (Open Source) by Modeliosoft

C3. Papyrus (Open Source) by The Eclipse Foundation

C4. Visual Paradigm by Visual Paradigm

C5. Mathlab Simulink and System Composer by The MathWorks

C6. Cameo Systems Modeler by Dassault Systèmes

C7. CORE by Vitech

C8. GENESYS by Vitech

C9. Wolfram SystemModeler By Wolfram Research

C10. Enterprise Architect by Sparx Systems

The first criteria investigated for these options are whether they are free to use by students participating in future HYPSO projects. The budget of the HYPSO projects are limited, and it is important to the implementation of the software that they can be used as student or research licenses. Each alternative was investigated and the vendors contacted to discover which alternatives were eligible.

Alternatives 1-8 were available for student of research licenses, while alternatives 9 and 10 were not. The first eight alternatives were available through research agreements with the vendor if no student licenses were found available online. The final two alternatives are dropped for further investigation. Three additional alternatives were considered earlier in the process of the trade-off study, but were later removed. This is further discussed in chapter 5.1. The next section compares the alternatives using the AHP method.

### 4.3.4 Performing the Analytic Hierarchy Process

Our list of alternatives has been reduced and we can begin comparing the different options. As described in chapter 3.2 we will use the AHP method to perform this comparison. We begin the process by evaluating the importance of each of the criteria. Each criteria weighs differently on the decision of choosing a software and it weighs differently for each individual stakeholder in the project. The different team leaders of HYPSO are referred to as stakeholders for the purposes of performing the AHP method. In addition to the team leaders interviewed in chapter 4.1, the project manager of HYPSO has also been asked to contribute to the weighing of the criteria. The author of this thesis has also contributed with his thoughts on the weighing of options. In total, five stakeholders are presented with giving their feedback on the importance of the criteria. The results are presented in the following figure with explanation in the following paragraph.

Figure 2 shows the final results of the weighing of criteria per the reflections of the stakeholders. The individual results have been added to appendix D. Each criterion has been given a weight

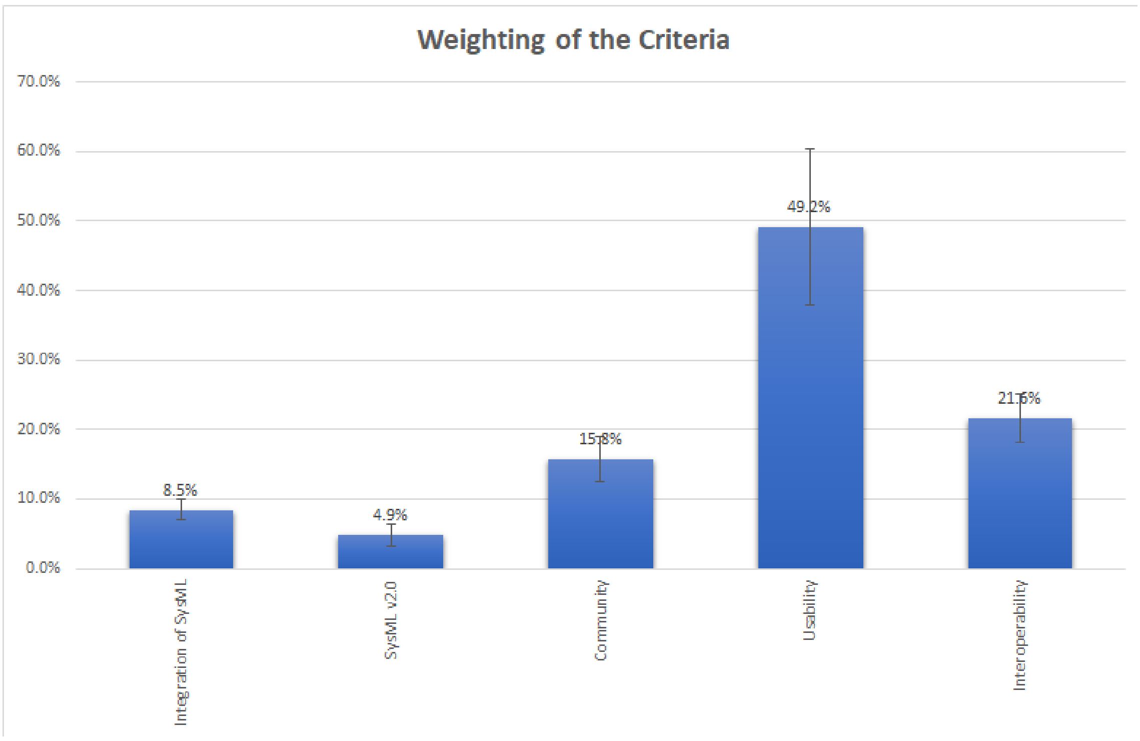
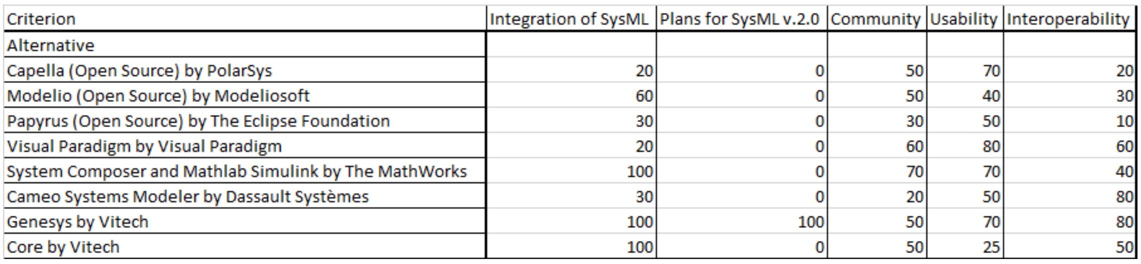


Figure 2: This figure shows the results from the AHP study after five of the stakeholders gave their reflections

which describes its overall importance compared to the other criterion on a scale of 0-100 percent. The results of each criterion is given with a measure of confidence indicated by the brackets at the top of each bar. We can conclude from these findings that the SysML-criteria do not score highly with the stakeholders, while Usability is important to all stakeholders. Usability will be essential in implementing the chosen software in the HYPSO project and allowing members to quickly grasps its features and potential. This means that Usability will dictate to a larger extent than other criteria how suitable any given alternative is for the HYPSO project. Now that the weighing of the criteria has been completed, it is necessary to evaluate the utility of each of the alternatives.

The utility of any alternative illustrates how well it performs in meeting with the criteria of the trade-off study. Each alternative will be judged on its ability to meet with each of the criteria. The alternatives are then given a score on a scale representing the criterion investigated. Then the scores will be converted into a scale using standardised units called utiles. Utiles is a unitless measure of utility. In this way each alternative can be given a score on a scale from 0-100 which can be compared to the other alternatives. The results of this look into the utility of each alternative is presented in figure 3.



| Criterion | Integration of SysML | Plans for SysML v.2.0 | Community | Usability | Interoperability |
|---|---|---|---|---|---|
| Alternative | | | | | |
| Capella (Open Source) by PolarSys | 20 | 0 | 50 | 70 | 20 |
| Modelio (Open Source) by Modeliosoft | 60 | 0 | 50 | 40 | 30 |
| Papyrus (Open Source) by The Eclipse Foundation | 30 | 0 | 30 | 50 | 10 |
| Visual Paradigm by Visual Paradigm | 20 | 0 | 60 | 80 | 60 |
| System Composer and Mathlab Simulink by The MathWorks | 100 | 0 | 70 | 70 | 40 |
| Cameo Systems Modeler by Dassault Systèmes | 30 | 0 | 20 | 50 | 80 |
| Genesys by Vitech | 100 | 100 | 50 | 70 | 80 |
| Core by Vitech | 100 | 0 | 50 | 25 | 50 |

Figure 3: This figure shows the overview of how each alternative scores in terms of utility for each criterion.

Figure 3 shows how each of the alternatives score in terms of utility on a scale from 0-100. Higher scores mean that the alternative offer more complete utility for the relevant criterion. The scores are given by the author after investigating the available documentation of each alternative. All the information is gathered from the official web pages dedicated to each alternative. The scores are given so that the alternatives are compared to each other and the scores reflects if a given alternative perform better or worse on the given criterion. Integration of SysML is graded based on which versions of SysML is supported and if the alternative supports the latest version. Plans for SysML 2.0 can only score 0 or 100 given the vendors plans for the software. Community scores better if the alternative provides support centres and active forums with high activity and a large number of active users. Usability is rated based on the number and quality of available tutorials and guides, and is partly affected by the Community score. Interoperability is rated higher if it provides an API or plug-in API to support the transfer of data between software, and even higher if it provides support for different modelling languages and for interaction between other MBSE software.

These scores are now used to find the total utility for each of the alternatives, which will tell us the alternative that best meets both the subjective weighing of the criteria by the stakeholders and the more objective utility of the alternatives. The total usability of the alternatives are presented in figure 4 below.

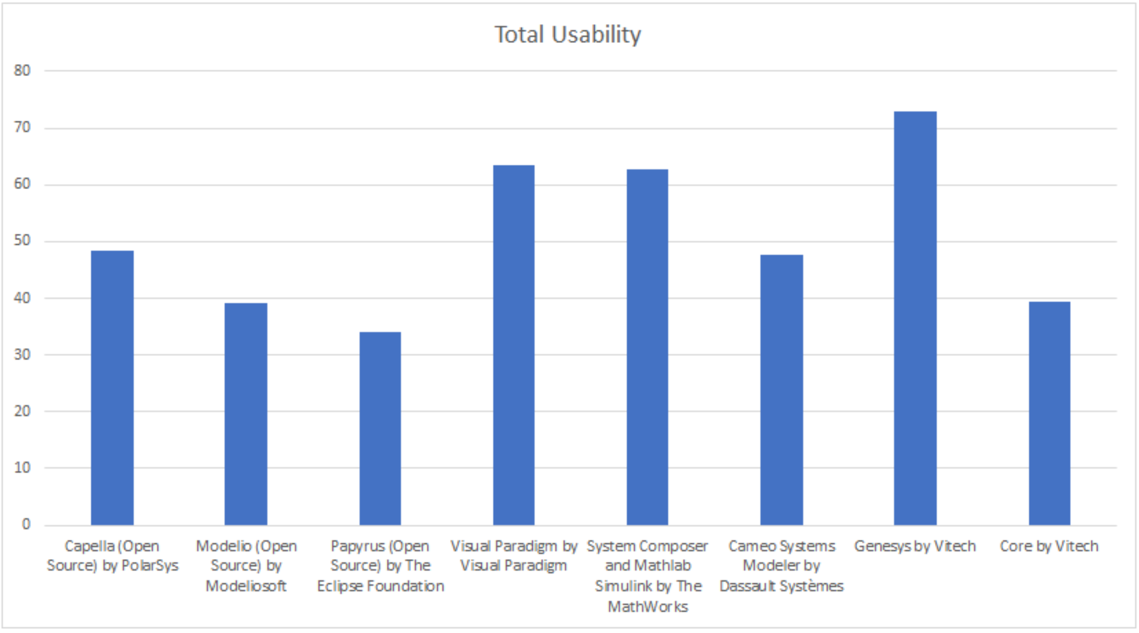


Figure 4: This figure shows the total scoring for each alternative, taking into account the weighing of the criteria and the utility of each alternative.

As we can see from figure 4, most of the alternatives end up with decent scores. Most of the alternatives meet the objectives satisfyingly, but some are rated more highly than others. Visual Paradigm, and the combination of System Composer and Simulink score highly in most criteria and are only outdone by Genesys. Genesys scores highly in most of the criteria, especially in the integration of SysML, Usability and Interoperability.

### 4.3.5 Conclusion of the Trade-off Study

Genesys by Vitech offers a complete package in terms of software capabilities and usability. The software supports SysML and have plans to integrate SysML v2.0 as it releases. It also scores well on usability as it offers many tutorials, guides and full documentation of the inner workings of the software. Genesys was the alternative that offered the most complete package in guidance and tutorials ready for new users to learn the software. It also provides Open API to support interoperability, as well as implemented support for Simulink.

The results of the trade-off study are discussed in chapter 5.1, where it will be highlighted the potential weaknesses of this study. The results are also discussed in chapter 5.2 to highlight the challenges in implementing Genesys for use by team members in HYPSO-2.

# 5 Discussion

## 5.1 Discussing the Results from the Trade-off Study

The trade-off study presented ten alternatives which were reduced to eight after checking the availability of research or student licenses. The number of alternatives could have been larger for this study, to further affect the outcome and allow for other suitable alternatives. It is not possible for the study to investigate every available software, but the number of alternatives could arguably have been higher. Some alternatives were removed as options as they were poor in providing relevant information. Three options, namely Innoslate by Innoslate, Rational Rhapsody by IBM and Scade by ANSYS were dropped as alternatives, as their vendors provided little irrelevant information online and gated the information. They were also unable to answer questions asked of their support departments.

The AHP method has some parts of it that will affect the outcome of the study. The weighting of the alternatives are affected by the number of participants. For the number of available stakeholders, the total weighting of the criteria should be accurate to the needs of the stakeholders. The utility study is also subjective in nature. To capture scores that would reflect more accurately the actual strengths of the alternatives, the utility study was performed twice. The results were compared and investigated if there were major discrepancies. The final results should accurately reflects how the alternatives compare to each other.

The criteria are created from the objectives of the trade study. If the objectives miss the goal of the project, they will lead to inaccurate criteria. The criteria can also be missing the mark in representing the objectives. It is difficult to know if both objectives and criteria are accurate in describing the goals of the project. They have led to a final result in choosing a tool that has been identified as being suitable for the needs of HYPSO members, which should verify that the objectives and criteria are accurate enough to produce satisfying results.

The trade-off study and its results answer the first research question presented in the thesis, repeated here to remind the reader.

R1. How adaptable are different available MBSE software for use in a student CubeSat project and which ones are best suited for use in coming HYPSO projects?

It has been identified that Genesys by Vitech is the best suited, with Visual Paradigm and the combination of System Composer and Simulink being suitable alternatives as well. The critical criteria for stakeholders in determining how adaptable different software are was identified as Usability. The alternatives that scored the lowest had the lowest Usability scores, indicating that this should be the deciding factor in choosing an alternative.

## 5.2 Discussing Overhead for use of MBSE software for HYPSO Projects

This sections discusses the considerations that must be made when implementing MBSE as a working methodology and tool in a project. The considerations are relevant to the second research question of this thesis, repeated here to remind the reader.

R2. How can MBSE help improve transdisciplinary communications and the design of scientific components?

The implementation of MBSE requires team members to be willing to adapt to a new way of working and documenting their work and results. The process of implementing MBSE is well documented in (Bonnet et al. 2015). The first obstacle to overcome is the cultural change required by the team members. Engineers are typically accustomed to working and documenting using the office suite or the google suite. By introducing an MBSE software, they are asked to change part of their fundamental working method. This requires the software to be implemented in the correct way for members to adjust to the new methodology.

In order for team members to adjust to a given MBSE software, a manager of the software is typically required. How well the member adjusts rely heavily on management and how management can guide and tutor the new users in implementing the new software in their work. A manager who would operate as a super user would be responsible for creating a plan for implementing the software, and guiding the users through set-up and learning how to use method and the software. Implementation will cost time from the project and it is critical that the manager is confident in their capabilities with the software so they can help new users adapt quickly. The manager needs to be part of the team during the entirety of the project to provide further guidance and tutoring.

It is essential that the chosen software is suitable to the users' needs. As the main focus of implementing MBSE in the project is to adapt to a new working methodology, the software should be easy to learn and should clearly build upon the principles of MBSE. The manager of the project should feel comfortable with the software to provide guidance when new users face difficulties and find the tool lacking in capabilities. Should the software not provide the necessary tools, users might feel tempted to return to old working methods, ignoring the benefits of MBSE. If the software is too difficult to learn, it defeats the purpose of implementing MBSE, where the focus should be on the method.

The project would benefit from implementing MBSE in different ways. MBSE generates engineering artefacts from models which in turn provide the foundation for improved design development. It generates a clear link to the requirements, easily conveyable documentation of the work, and has a focus on developing a clear goal before focusing on the exact technological solution. Documentation is presented graphically, improving the exchange of information between disciplines, and allows for documentation to be stored in one place. Through profiles, the software can typically offer different perspectives which opens the information only to those who have need for it, removing any unnecessary information. This improves communications between members of the project, benefiting the overall design development.

## 5.3 Discussing the Results from the Bootloader Model

This section discusses the results from the modelling of the Bootloader using Capella. The creation of this model is directly relevant to the third research question presented in the thesis. The research question is repeated here for simplicity.

R3. How can MBSE be used to implement a model for future project management through reverse engineering of existing project data?

The work presented in chapter 4.2 shows how a model can be implemented in a way that has value to team members and how the work can be performed for future elements of HYPSO projects. The model was implemented in a reasonable amount of time, estimated at 25 hours. This implementation was performed by the author with no prior experience using MBSE software, and includes the time spent learning to use Capella. The model proves helpful both in showing how models can be used as verification for code that is being worked on, and in verifying the implementation after the code has been written. The Bootloader itself was a piece of code of low complexity, but it still had elements of redundancy and potential errors. Going forward to the next HYPSO project, code can be modelled using MBSE before attempting to write it, which would prove especially helpful with complex code. The team leader of On-board Processing Algorithms was asked whether modelling such as the one performed for the Bootloader could be considered helpful in coding, and confirmed that it could. Using models to verify and implement code was not done for the work done on the current HYPSO project, but it would help if time was spent on learning to use the tools before starting to code. For the next HYPSO project, this thesis recommends implementing MBSE software early in development as a tool for verifying code.

This thesis argues that spending time learning to use the MBSE software will be worth it for programming. The models make the logic of the program more accessible to coders who have not worked directly on the code before. The model uses a graphical language that conveys meaning more effectively than the code itself. In this way, the model can function as documentation of the code, making it more accessible to those who try to understand the code at a later stage in development. The model opens the code for users who are not familiar with the programming language as well. Models can usually be shared with read access to team members who are not working on coding. In the case that code interacts with components of other teams on the project, the model can be used to improve communications. Where code written in an unfamiliar programming language can be difficult to understand, the models usually convey information and meaning when they are modelled correctly. The graphical language ensures that it is accessible to anyone and helps verify that the necessary interactions are available in the code. By making the information more accessible it eases the transdisciplinary flow of communication, which in turn can affect design decisions favourably. Design decisions are improved by sharing knowledge so that it is accessible to teams besides those performing the coding. Increased knowledge and an increase in understanding should affect design decisions positively, as touched upon in chapter 2.8.

The modelling has been checked for sources of errors that could lead to misleading results. The main sources of error would be a misunderstanding on how the Bootloader is implemented which would give errors in the model, and that the uses for such a modelling tool have been exaggerated by the author. The model was presented for the team leader for System Integration and Electronics to check if it complied with the existing Bootloader code. The team leader was given an in depth presentation of the model and gave feedback. The model was highly accurate in modelling the preexisting code and parts were changed if something did not match the code. Only minor adjustments were made to fully comply with the team leaders understanding of the code. This acted as the verification of the work done and ensures that the model is accurate. To check if modelling can be of use in implementing code, the team leader of On-board Processing Algorithms was asked for thoughts on the matter. The team leader verified that the tool would be useful in creating code if it was introduced correctly and the programming team was introduced to modelling as a method for producing new code. In conclusion, the results have been verified by team leaders with relevant experience to give appropriate feedback which helps the validity of the results.

# 6 Conclusion and Further Work

This thesis presented three research questions which have been answered. They are repeated here to identify the conclusions drawn when investigating them.

R1. How adaptable are different available MBSE software for use in a student CubeSat project and which ones are best suited for use in coming HYPSO projects?

The trade-off study concluded that there are some suitable software out of the alternatives presented. Genesys by Vitech was identified as the best alternative, meeting the criteria in a satisfying way. Genesys has a strong implementation of SysML and scores highly in Community, Usability and Interoperability. The stakeholders of the project identified Usability as the critical criterion and Genesys has guides and tutorials available for new user. Besides Genesys, Visual Paradigm by Visual Paradigm and the combination of System Composer and Simulink by The MathWorks were identified as also being suitable for use in coming HYPSO projects.

R2. How can MBSE help improve transdisciplinary communications and the design of scientific components?

Team Leader Interviews identified the need for improved communications and sharing of information. MBSE software allows for integration with third-party software which can automatically update information for the users. The HYPSO project continues to grow in complexity and size and MBSE software can play a role in validating information and acting as documentation for the work done. The method of development of new products related to MBSE can be implemented to strengthen design development. A manager of MBSE would be required to guide and tutor users in both methodology and using a new software.

The implementation of models from MBSE can open up sharing of knowledge across disciplines. The graphical language of models makes code more accessible to those without coding experience. Making knowledge more accessible to other teams can affect design decisions favourably.

R3. How can MBSE be used to implement a model for future project management through reverse engineering of existing project data?

Capella was used as an MBSE software to implement existing project in form of the Bootloader code. The Bootloader code was analysed and modelled as an example of how it could be done, to demonstrate how long it would take, and to identify strengths of modelling with MBSE. The work was performed in approximately 25 hours when including the time to learn to use Capella with no prior knowledge. The model was validated by the team leader of System Integration and Electronics and the team leader of On-board Processing Algorithms verified that such model would be relevant in validating and producing code. MBSE modelling can be used as a tool for improving and validating the work on complex code.

For future work, this thesis identifies the need for an MBSE manager that would guide and tutor members in the use of the chosen software. In order to take advantage of the possibilities of MBSE, someone needs to be responsible for implementing MBSE as a working methodology for HYPSO members. The aim should be to allow team members to document their work in the chosen MBSE software and to use the modelling tools for coding and physical architecture. MBSE offers a different methodology of developing new products and this thesis recommends incorporating the use of MBSE software at the beginning of the semester to benefit the most from implementation.

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# Appendix

## A Interviews with HYPSO Team Leaders

Interviews were carried out according to the process described in chapter 3.1. These were the results of the interviews.

The interviews were done with the team leaders of HYPSO, according to the following overview:

1. Team Leader of Mechanics
2. Team Leader and Coming Team Leader of ADCS
3. Team Leader of On-board Processing Algorithms
4. Team Leader of System Integration and Electronics and Team Leader of Operations

It is recommended to have the list of questions from chapter 3.1 at hand to see what is being answered.

### A.1 Interview with Team Leader of Mechanics

Q1. Anything hardware related that needs a physical model is build by the mechanics team. This includes the components of the payload, test benches used for validating the performance of components and in part the on-board electronics. Test benches are needed to validate and perform thermal analysis, testing for shock and vibrations, environmental tests and vacuum testing. The mechanics team is also responsible for performing the tests and writing reports on their findings.

Further responsibilities of the mechanics team include the ordering of parts, building the cameras, performing radiation tests of the equipment and doing spectral calibration using software. There is also a optical model of the camera which is used for analysing tolerances of the camera. They are also responsible for ensuring centre of mass and the total mass complies with requirements.

The mechanics team primarily communicate with the On-board Processing Algorithm team, the System Integration and Electronics team and the Missions team. The On-board Processing Algorithm team is needed for the Flight-model, the System Integration and Electronics team for the electronics hardware and the Missions team for simulations.

Q2. Python is used for spectral calibration of the camera. Siemens NX is used for simulations of the hardware. Thermal analysis is performed using ESATAN-TMS.

Q3. Information is stored in text documents and spread sheets on Google Drive and data and information is shared on Slack. There is a server for storing photos and information from the camera. It is pointed out during the interview that it can be difficult for members to access information that other members have. The situation described was information regarding a 3D model made for 3D printing. The information regarding the model dimensions was only available to the member who had created the model.

Q4. Through Microsoft Office and Google Docs Suite

Q5. Usually shared over Slack.

### A.2 Interview with Team Leader and Coming Team Leader of ADCS

Q1. To improve and enhance the capabilities of the existing ADCS systems of the satellite. The ADCS system is used to determine the positioning of the satellite in orbit and to know the orientation of the satellite in regards to the ground. The position of the satellite is determined in relation to ground stations on earth. The satellite uses several components to keep track of its position and orientation, such as GPS, light sensors to determine light intensity and direction, gyroscopes, star tracker to map orientation according to star maps and sensors to measure the magnetic fields of earth. To control the orientation of the satellite, reaction wheels, magnetic torques and small rockets are used.

The ADCS team is primarily reliant on the Operations team to know which maneuvers to perform when.

Q2. The ADCS team uses Matlab, Simulink, Python, SDK, and GitHub.

Q3. Work and results are presented in papers, articles through GitHub and through weekly meetings to discuss findings.

Q4. Information is directly shared with NanoAvionics.

### A.3 Interview with Team Leader of On-board Processing Algorithm

1. What are the goals and responsibilities of your team?
    - (a) Develop software to be deployed on the target hardware
    - (b) Develop software to be used for testing/profiling of payload software
    - (c) Documentation of software; Usage and implementation
    - (d) Close ties to Operations, Electronics and Mechanical
    - (e) Operations: meeting the operational requirements as best as possible for the HW
    - (f) Electronics: Co-defining the requirements for the target hardware, adhering
    - (g) Mechanical: Test support
2. What software/programs does your team use?
    - (a) GitHub; distributed version control and source code management, bug tracking, feature requests, task management
    - (b) Jenkins; continuous integration with hardware-in-the-loop (HIL)
    - (c) Slack; communication
    - (d) Various IDEs; Dependent on developer preference
    - (e) Docker; virtual machine
3. What are the working methods used by your team – how does the team members organize their work?
    - (a) Task management via GitHub
    - (b) Weekly meetings; Status report
    - (c) Bi-weekly sprint; Planning
4. How does the team members store their data and their work?
    - (a) Locally, and then by pushing to the common server hosted by GitHub
    - (b) Drive
5. How does the team members share their data with other teams?
    - (a) bug tracking, feature requests, and pull requests via GitHub
    - (b) Operations - To be able to develop the operational procedures that is supported by the payload
    - (c) Mechanical - To be able to test the payload performance
    - (d) Electronics - To know what is needed in terms of PCB and how it shall be included
    - (e) Management - Outreach

## A.4 Interview with Team Leader of System Integration and Electronics, and Team Leader of Operations

1. What are the goals and responsibilities of your team?

   To operate the satellite to specified requirements and make sure everything operates correctly in space. There are two sides to the Operations team, which are the Ground Station and the Operations team, but they are organised as one. There is a need to know how the software and hardware of the satellite works. It is essential to stay up to date with how communications for the satellite work, which type of radio systems, protocols and interfaces are used.

2. What software/programs does your team use?

   Programs from the Microsoft Office and Google Suite and Simulations Systems Tool Kit.

3. How does the team members store their data and their work?

   Documentation and planning goes into Google Sheet and Google Docs.

4. How does the team members share their data with other teams?

   Information is shared with other teams over Teams on a weekly basis.

## B The Bootloader Model in Capella

Figures 5 and 6 shows the model of the Bootloader that was created in Capella. Together the two figures create a complete overview of the model. The model is explained in chapter 4.2. The figures should be available for reading to follow along the explanations presented in chapter 4.2.

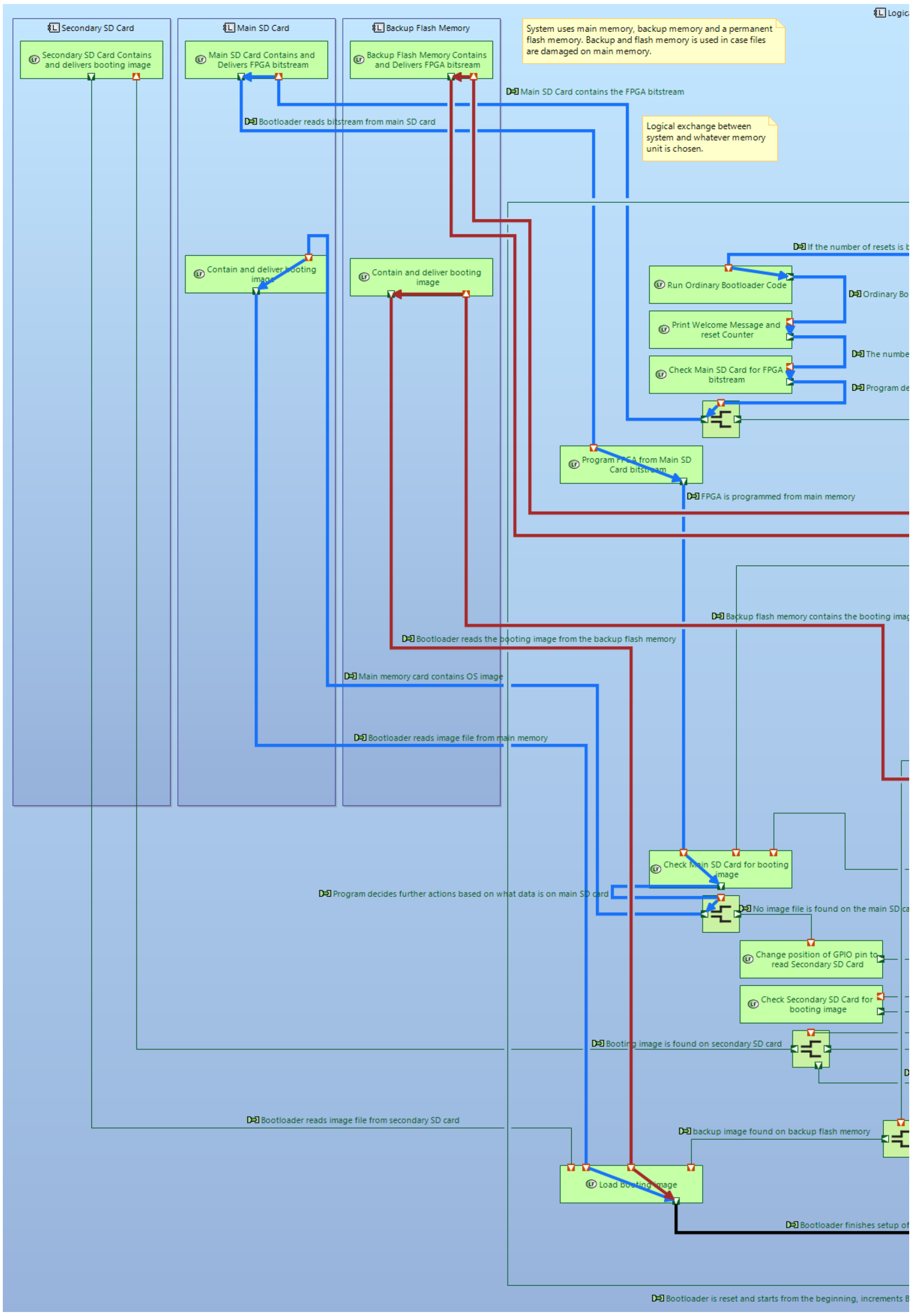
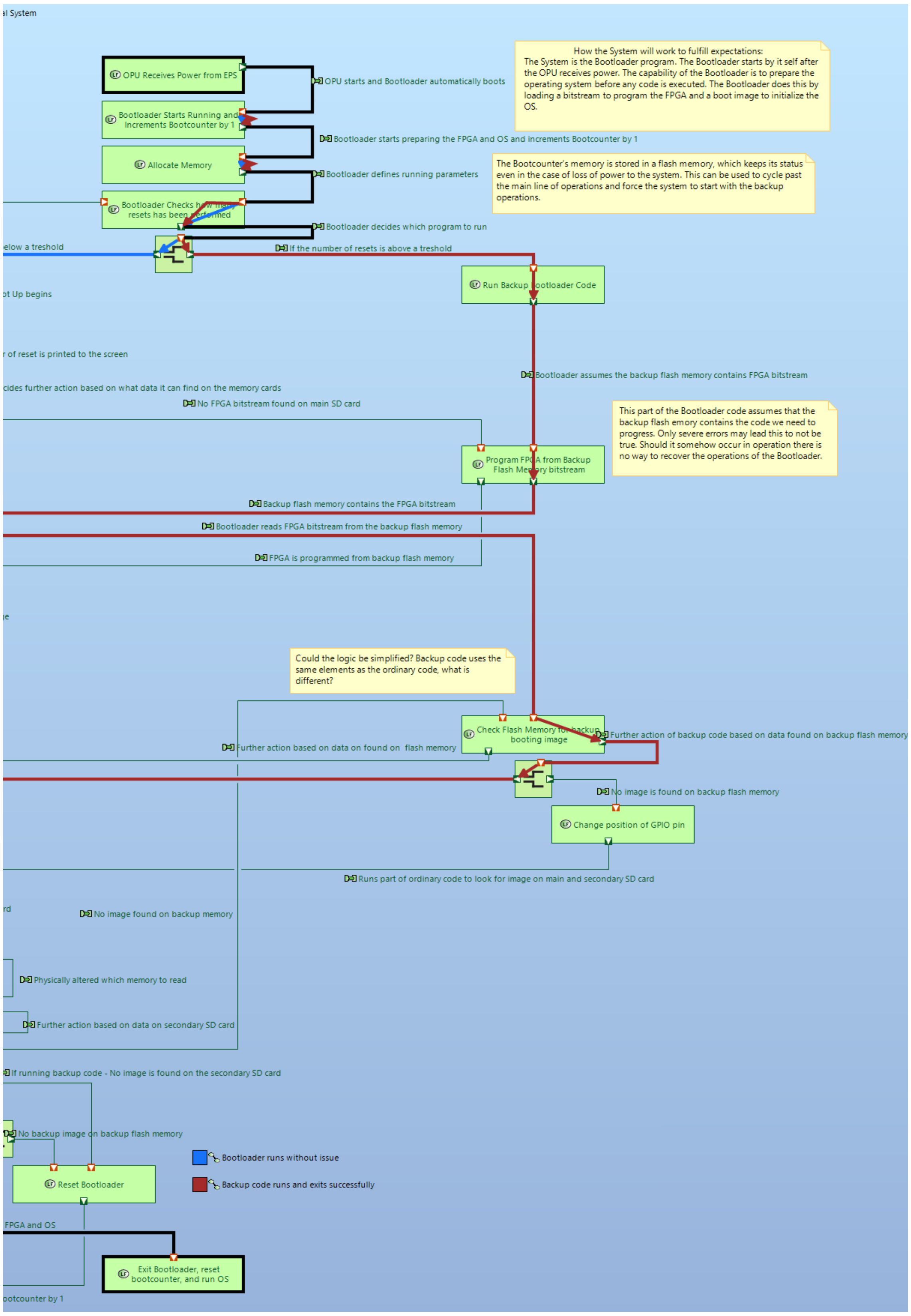

Secondary SD Card
Secondary SD Card Contains and delivers booting image
Main SD Card
Main SD Card Contains and Delivers FPGA bitstream
Backup Flash Memory
Backup Flash Memory Contains and Delivers FPGA bitsream
System uses main memory, backup memory and a permanent flash memory. Backup and flash memory is used in case files are damaged on main memory.
Logic
Main SD Card contains the FPGA bitstream
Bootloader reads bitstream from main SD card
Logical exchange between system and whatever memory unit is chosen.
If the number of resets is b
Contain and deliver booting image
Contain and deliver booting image
Run Ordinary Bootloader Code
Ordinary Bo
Print Welcome Message and reset Counter
The numbe
Check Main SD Card for FPGA bitstream
Program de
Program FPGA from Main SD Card bitstream
FPGA is programmed from main memory
Backup flash memory contains the booting imag
Bootloader reads the booting image from the backup flash memory
Main memory card contains OS image
Bootloader reads image file from main memory
Check Main SD Card for booting image
Program decides further actions based on what data is on main SD card
No image file is found on the main SD ca
Change position of GPIO pin to read Secondary SD Card
Check Secondary SD Card for booting image
Booting image is found on secondary SD card
D
Bootloader reads image file from secondary SD card
backup image found on backup flash memory
Load Booting image
Bootloader finishes setup of
Bootloader is reset and starts from the beginning, increments B

Figure 5: View of the Bootloader model in Capella - First Half


al System
OPU Receives Power from EPS
OPU starts and Bootloader automatically boots
Bootloader Starts Running and Increments Bootcounter by 1
Bootloader starts preparing the FPGA and OS and increments Bootcounter by 1
Allocate Memory
Bootloader defines running parameters
Bootloader Checks how many resets has been performed
Bootloader decides which program to run
elow a treshold
If the number of resets is above a treshold
Run Backup Bootloader Code
ot Up begins
r of reset is printed to the screen
Bootloader assumes the backup flash memory contains FPGA bitstream
cides further action based on what data it can find on the memory cards
No FPGA bitstream found on main SD card
Program FPGA from Backup Flash Memory bitstream
Backup flash memory contains the FPGA bitstream
Bootloader reads FPGA bitstream from the backup flash memory
FPGA is programmed from backup flash memory
e
Check Flash Memory for backup booting image
Further action of backup code based on data found on backup flash memory
Further action based on data on found on flash memory
No image is found on backup flash memory
Change position of GPIO pin
Runs part of ordinary code to look for image on main and secondary SD card
rd
No image found on backup memory
Physically altered which memory to read
Further action based on data on secondary SD card
If running backup code - No image is found on the secondary SD card
No backup image on backup flash memory
Reset Bootloader
FPGA and OS
Exit Bootloader, reset bootcounter, and run OS
ootcounter by 1

How the System will work to fulfill expectations:
The System is the Bootloader program. The Bootloader starts by it self after the OPU receives power. The capability of the Bootloader is to prepare the operating system before any code is executed. The Bootloader does this by loading a bitstream to program the FPGA and a boot image to initialize the OS.

The Bootcounter's memory is stored in a flash memory, which keeps its status even in the case of loss of power to the system. This can be used to cycle past the main line of operations and force the system to start with the backup operations.

This part of the Bootloader code assumes that the backup flash emory contains the code we need to progress. Only severe errors may lead this to not be true. Should it somehow occur in operation there is no way to recover the operations of the Bootloader.

Could the logic be simplified? Backup code uses the same elements as the ordinary code, what is different?

🟦 Bootloader runs without issue

🟥 Backup code runs and exits successfully

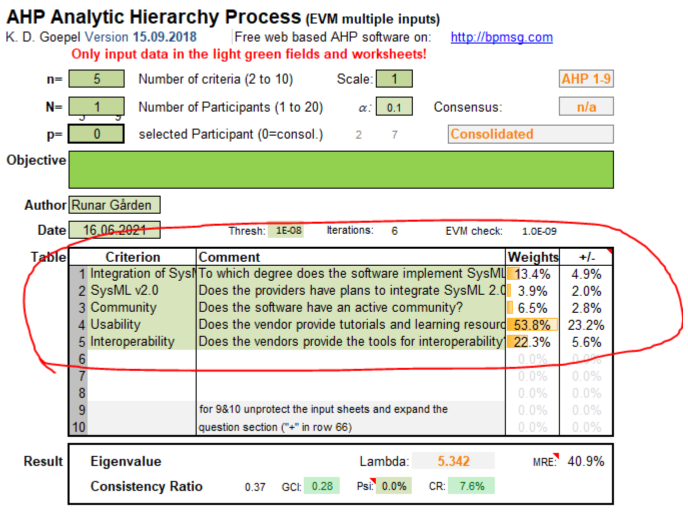
Figure 6: View of the Bootloader model in Capella - Second Half

## C Using AHP Excel Spreadsheet in Norwegian

AHP går ut på å gjøre et valg ved hjelp av kriterier og på bakgrunn av interessene til de som styrer prosjektet valget er relevant for. I dette tilfellet skal jeg velge en MBSE software, og har laget noen kriterier til hva programmet må oppfylle. Dersom du har mulighet til å hjelpe må du ta stilling til hvor viktig hvert enkelt kriterium er for deg i valg av en MBSE software. Dersom dere ikke har noe forhold til hvor viktig/uviktig et kriterium er, ranger det lite viktig.

Kriteriene jeg har laget meg er: Kriterium 1: Integrering med SysML – At softwaren bruker SysML som et av sine modelleringsspråk. Kriterium 2: Planer for å integrere SysML 2.0 – SysML versjon 2.0 er like rundt hjørnet og det er ønskelig at programmet har planer om å bygge på den oppdaterte versjon av SysML. Kriterium 3: Community: At det finnes en aktiv brukergruppe og software support som kan bidra med hjelp dersom noe er uklart eller man ikke får til å bruke programmet slik man har tenkt. Kriterium 4: Usability: At programmet er tilrettelagt for nye brukere og at opplæring i programmet er en del av tilbudet fra de som gir ut programmet. En del av dette er at det finnes guider, videoer man kan følge og dokumentasjon på hvordan programmet fungerer. Kriterium 5: Interoperability: At programmet tilrettelegger for å kunne utveksle informasjon med andre program. Det kan være at det finnes tilgang på API, eller at det allerede tilrettelegger for å utveksle info med program som er relevante for HYPSO, f.eks. Simulink, Siemens NX, Python.

Videre følger forklaring på bruk av excel-dokumentet.



**AHP Analytic Hierarchy Process** (EVM multiple inputs)
K. D. Goepel Version 15.09.2018 | Free web based AHP software on: http://bpmsg.com
Only input data in the light green fields and worksheets!

| | | | | | |
|---|---|---|---|---|---|
| n= | 5 | Number of criteria (2 to 10) | Scale: | 1 | AHP 1-9 |
| N= | 1 | Number of Participants (1 to 20) | α: | 0.1 | Consensus: n/a |
| p= | 0 | selected Participant (0=consol.) | 2 | 7 | Consolidated |

Objective

Author: Runar Gården
Date: 16.06.2021 Thresh: 1E-08 Iterations: 6 EVM check: 1.0E-09

| Table | Criterion | Comment | Weights | +/- |
|---|---|---|---|---|
| 1 | Integration of SysI | To which degree does the software implement SysML | 13.4% | 4.9% |
| 2 | SysML v2.0 | Does the providers have plans to integrate SysML 2.0 | 3.9% | 2.0% |
| 3 | Community | Does the software have an active community? | 6.5% | 2.8% |
| 4 | Usability | Does the vendor provide tutorials and learning resourc | 53.8% | 23.2% |
| 5 | Interoperability | Does the vendors provide the tools for interoperability | 22.3% | 5.6% |
| 6 | | | 0.0% | 0.0% |
| 7 | | | 0.0% | 0.0% |
| 8 | | | 0.0% | 0.0% |
| 9 | | for 9&10 unprotect the input sheets and expand the | 0.0% | 0.0% |
| 10 | | question section ("+" in row 66) | 0.0% | 0.0% |

Result
Eigenvalue Lambda: 5.342 MRE: 40.9%
Consistency Ratio 0.37 GCI: 0.28 Psi: 0.0% CR: 7.6%

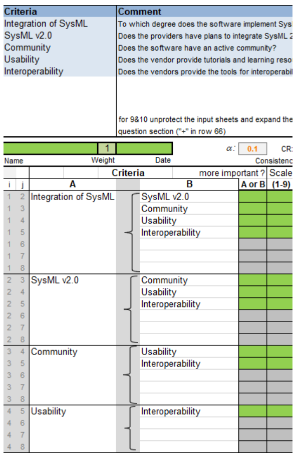
Figure 7:
fig:overviewweighting

Ringet rundt i rødt er den infoen som er av interesse. Dette er de fem kriteriene som programmet tar stilling til. Oppgaven din blir å vektlegge hvert enkelt kriterium opp mot hverandre. I excelarket finnes flere faner, og du starter med å åpne fane «ln2». Inne i fanen ser du dette:

Et eksempel på hvordan det er fylt ut finnes i fanen «ln1». I den øverste boksen, hvor det står «Integration of SysML» skal du vurdere de ulike kriteriene mot hverandre og deretter gi en karakter på hvor mye viktigere det ene kriteriet er enn det andre. Så først må du ta stilling til hva som er viktigst av «Integration of SysML» mot «Plans for SysML 2.0.» Deretter gi en karakter fra 1 til 9 på hvor mye viktigere. Dersom «Integration of SysML» er viktigst, velges A i kolonnen for «A or B». Dersom de to kriteriene er like viktige, velges enten A eller B og deretter karakter 1. Karakterskalaen er som følger:

Det er best om det kun brukes oddetallskarakterer. Når evalueringen er unnagjort kan arket se slik ut:

Dette gir beskjed om at noen av karakterene ikke er konsekvente med tidligere karakterer. I cellen hvor jeg har karaktersatt «SysML 2.0» mot «Community» har jeg gitt karakter 7 på viktighet, men dette er ikke konsekvent med andre karakterer. Programmet foreslår at jeg gir prioriterer B og gir karakter 7 i denne cellen. Alternativt må jeg tenke gjennom prioritering min en gang til. På denne måten blir alle kriterier sammenlignet opp mot hverandre og programmet hjelper til med å holde karakterene og prioritering konsekvent.



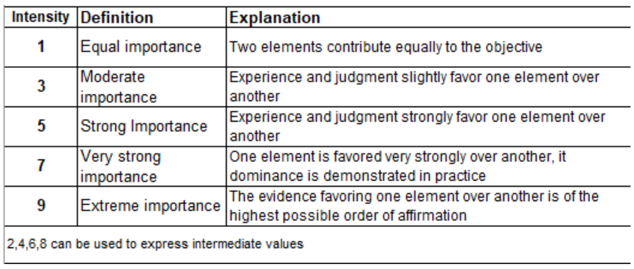
| Criteria | Comment |
|---|---|
| Integration of SysML | To which degree does the software implement Sys |
| SysML v2.0 | Does the providers have plans to integrate SysML 2 |
| Community | Does the software have an active community? |
| Usability | Does the vendor provide tutorials and learning reso |
| Interoperability | Does the vendors provide the tools for interoperabil |
| | for 9&10 unprotect the input sheets and expand the question section ("+" in row 66) |

1 α: 0.1 CR:

Name Weight Date Consistenc

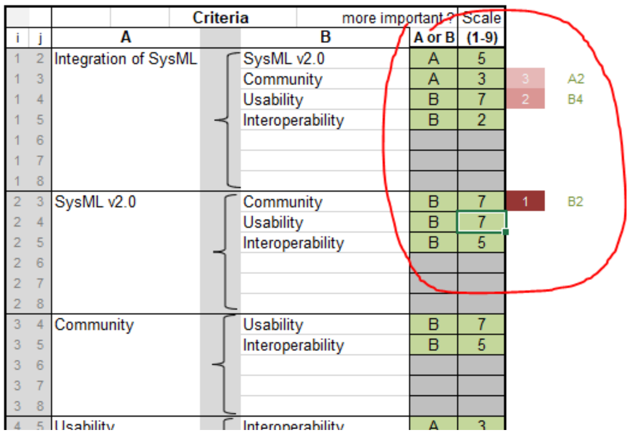
| | | Criteria | | more important ? | Scale |
|---|---|---|---|---|---|
| i | j | A | B | A or B | (1-9) |
| 1 | 2 | Integration of SysML | SysML v2.0 | | |
| 1 | 3 | | Community | | |
| 1 | 4 | | Usability | | |
| 1 | 5 | | Interoperability | | |
| 1 | 6 | | | | |
| 1 | 7 | | | | |
| 1 | 8 | | | | |
| 2 | 3 | SysML v2.0 | Community | | |
| 2 | 4 | | Usability | | |
| 2 | 5 | | Interoperability | | |
| 2 | 6 | | | | |
| 2 | 7 | | | | |
| 2 | 8 | | | | |
| 3 | 4 | Community | Usability | | |
| 3 | 5 | | Interoperability | | |
| 3 | 6 | | | | |
| 3 | 7 | | | | |
| 3 | 8 | | | | |
| 4 | 5 | Usability | Interoperability | | |
| 4 | 6 | | | | |
| 4 | 7 | | | | |
| 4 | 8 | | | | |

Figure 8:
fig:relevantpage



| Intensity | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two elements contribute equally to the objective |
| 3 | Moderate importance | Experience and judgment slightly favor one element over another |
| 5 | Strong Importance | Experience and judgment strongly favor one element over another |
| 7 | Very strong importance | One element is favored very strongly over another, it dominance is demonstrated in practice |
| 9 | Extreme importance | The evidence favoring one element over another is of the highest possible order of affirmation |
| 2,4,6,8 can be used to express intermediate values | | |

Figure 9:
fig:grading



| | | Criteria | | more important ? | Scale | | |
|---|---|---|---|---|---|---|---|
| i | j | A | B | A or B | (1-9) | | |
| 1 | 2 | Integration of SysML | SysML v2.0 | A | 5 | | |
| 1 | 3 | | Community | A | 3 | 3 | A2 |
| 1 | 4 | | Usability | B | 7 | 2 | B4 |
| 1 | 5 | | Interoperability | B | 2 | | |
| 1 | 6 | | | | | | |
| 1 | 7 | | | | | | |
| 1 | 8 | | | | | | |
| 2 | 3 | SysML v2.0 | Community | B | 7 | 1 | B2 |
| 2 | 4 | | Usability | B | 7 | | |
| 2 | 5 | | Interoperability | B | 5 | | |
| 2 | 6 | | | | | | |
| 2 | 7 | | | | | | |
| 2 | 8 | | | | | | |
| 3 | 4 | Community | Usability | B | 7 | | |
| 3 | 5 | | Interoperability | B | 5 | | |
| 3 | 6 | | | | | | |
| 3 | 7 | | | | | | |
| 3 | 8 | | | | | | |
| 4 | 5 | Usability | Interoperability | A | 3 | | |

Figure 10:
fig:errormessage

## D Weighting of the Criteria by the Stakeholders

Here is presented the weighing of the different criteria by five of the stakeholders in the HYPSO project. Most of the stakeholders valued usability highly, referring to the results presented in figures 11, 12, 14 and 15. Figure 13 shows how one of the stakeholders valued community over the other criteria. In chapter 4.3.4 the total weighing of the criteria based on these individual results are presented.

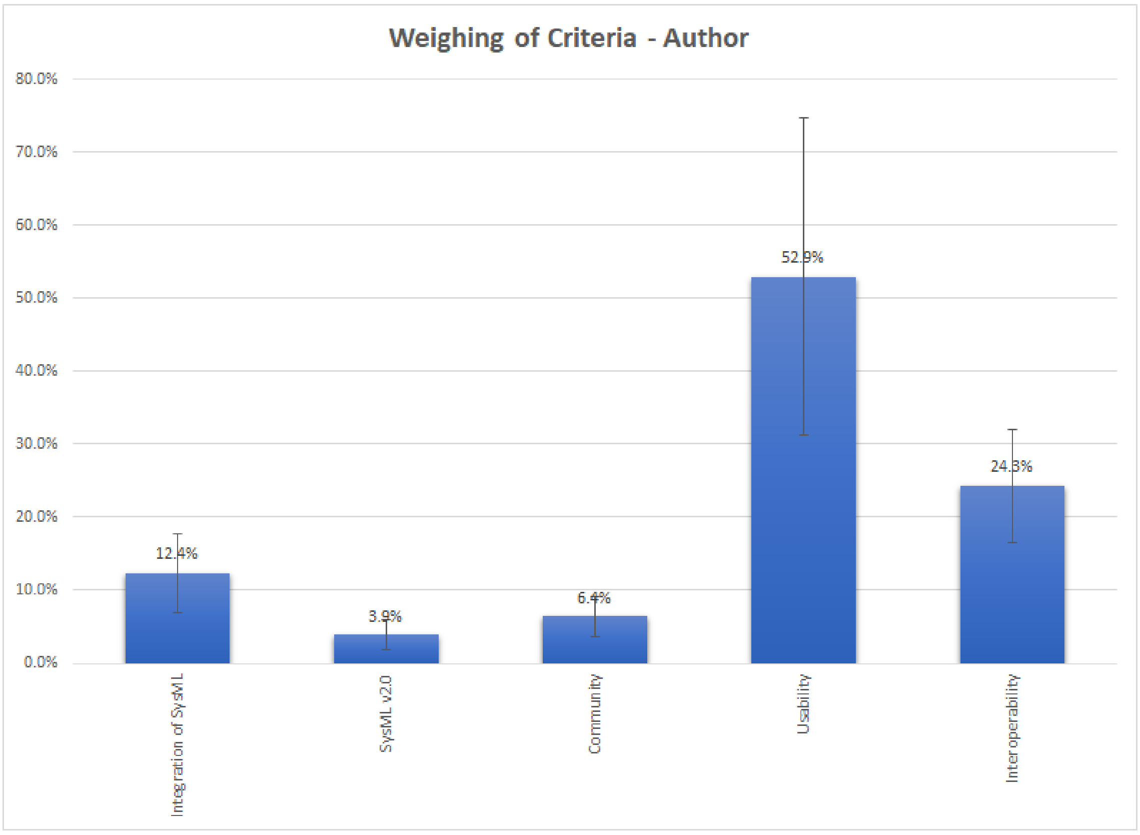


Figure 11: This figure shows the weighing of the criteria by the author. Community is prioritised and plans to incorporate SysML 2.0 is not of importance to the author.

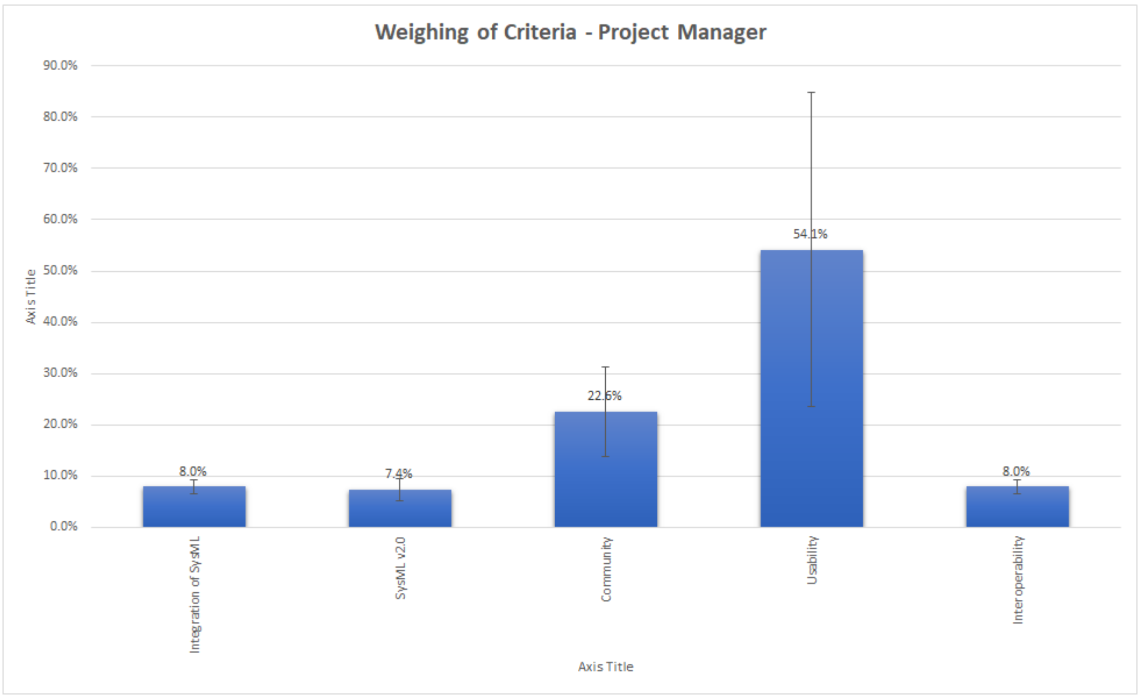


Figure 12: This figure shows the weighing of the criteria by the project manager. Community and Usability score highly.

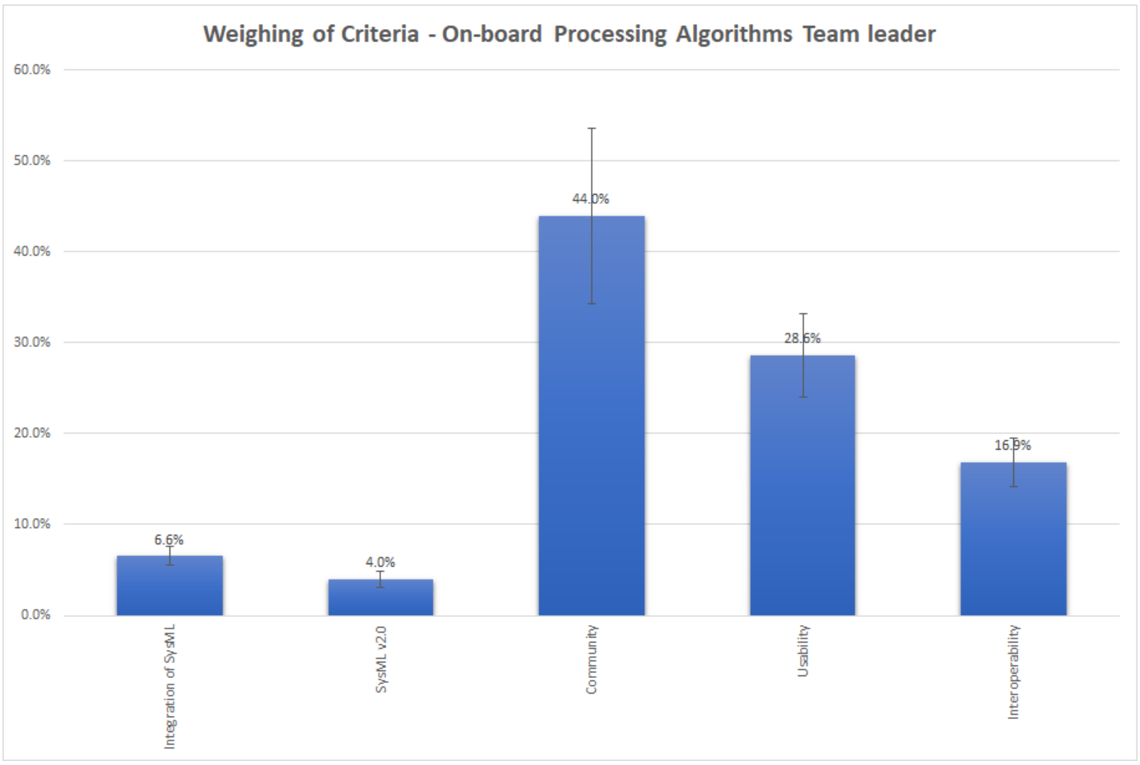


Figure 13: This figure shows the weighing of the criteria by the team leader of On-board Processing Algorithms. Community is highly valued, with usability as a second priority.

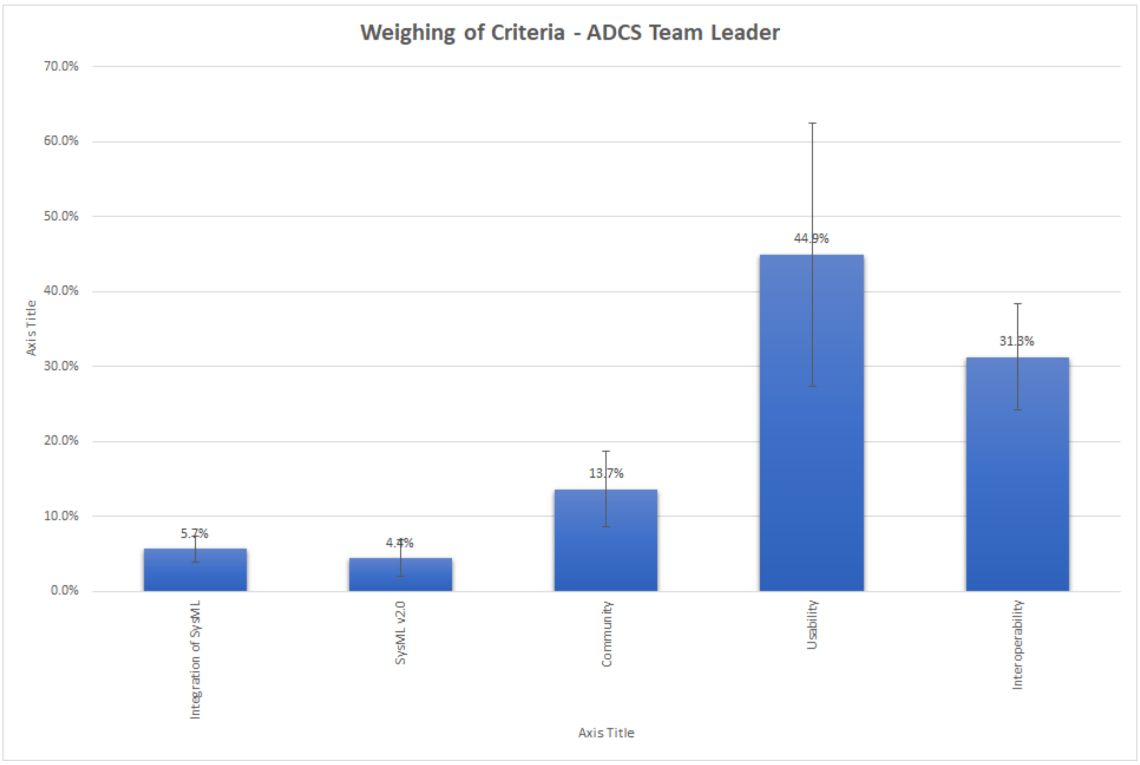


Figure 14: This figure shows the weighing of the criteria by the ADCS team leader. Usability is highly valued, with interoperability as a close second.

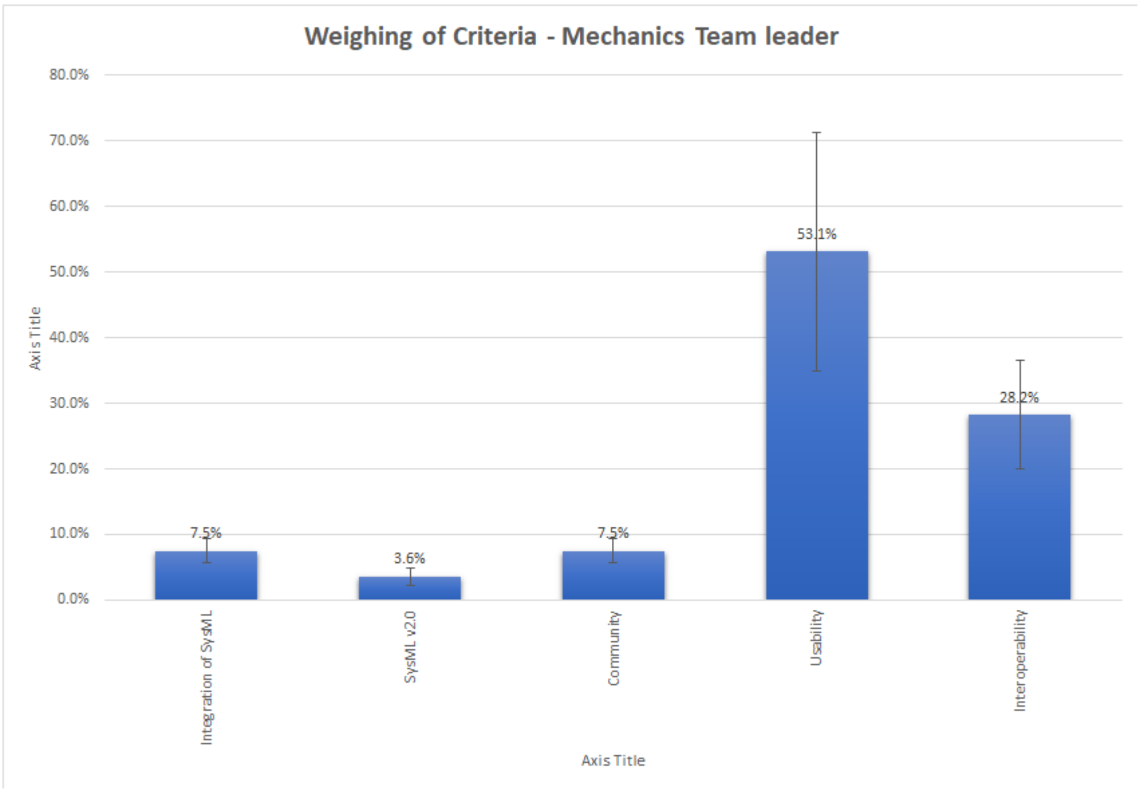


Figure 15: This figure shows the weighing of the criteria by the Mechanics team leader. Usability scored highly, while SysML and community was not prioritised.