Application of Model-Based Systems Engineering for the Integration of Electric Engines in Electrified Aircraft

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Abstract. The objective of green, carbon-neutral flights is propelling the innovation of newer propulsion systems. With this increased development of an interdisciplinary form of propulsion for aircraft, the integration burdens and efforts intensify. In literature, it is estimated that it takes 10-15 years to design and develop an aircraft. The expected date of entry for any hybrid electric aircraft is 2035-2040. Any innovation and effort to cut this time by any degree should be explored and analysed. One of the techniques that have the potential to help fast-track the research and development of interdisciplinary systems is Model-based System Engineering (MBSE). Various studies have shown the benefit of employing a model-based design strategy. The focus case study relates to the integration of the electric machine and the propeller, along with related sub-systems. For Hybrid Electric Propulsion (HEP), the electric machine and propeller need to be integrated and their interaction to be analysed. MBSE is proposed as a methodology that would help streamline the process of design and integration of the two systems. This study documents the exploration of connecting MBSE with current simulation and modelling of sub-systems in order to ensure the fulfilment of stakeholder needs and full system effectiveness. This paper establishes the research problem, and the approach to be pursued, and gives notice of first developments and expected follow-up work.

1. Introduction

Currently, the advance of complex systems and innovations is being moved to a transdisciplinary nature. Collaboration is needed at various levels between different partners and experts of different disciplines. With the involvement of multiple partners and disciplines, a need arises to ensure that the system is designed and developed coherently. With the increase in the contribution of carbon emission by the aviation sector newer means of propulsion are sought after, an option under study being hybrid electric propulsion. The use of an electric machine in the power train has the potential to reduce the burning of fuel, thus reducing carbon emissions. Such systems are complex in nature with technological contributions from multiple disciplines.

The complexities when designing a new type of aircraft or in this case, a propulsion system, are safety engineering, business and other trade-offs like efficiency, weight, power and maintenance must be taken into account with the full integration into the aircraft. The design parameters of

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the propulsion system and the aircraft are interconnected. Due to the transdisciplinary nature of research, technical experts from various domains will have to design this integrated system. This further adds to the complexity of the design process. MBSE is proposed as a solution to manage this complexity. There are various papers in the literature that talk about the usefulness of MBSE in a project. MBSE is used where the complexity of the system is large, there are many stakeholders from different fields and when the project's time duration is long.

In this paper, section 2 gives a brief description and explanation of MBSE. In section 3, the context of the undertaking is mentioned along with the objectives for this study and the hypothesis is also discussed. The methodology used in this paper and the rationality for the methodology chosen in mentioned in section 4. The workflow used for our use case is explained in section 5. Finally, the conclusion and the learning for further exploration are explained in section 6.

2. MBSE: Model Based System Engineering

MBSE is a full approach to Systems Engineering using digital models. MBSE is the formalized 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. [1]

MBSE utilises a database to capture and track the elements and their relationships with each other, rather than manually tracing from one segment of a document to either the same document or another document. It allows configuration management changes to be assessed for their impact a lot easier than paper-based approaches along with quickly generating diagrams, reports and other artifacts like requirements documentation automatically.

Manual traceability of the requirements introduces human error. Overall, the document-based approach can be quite rigorous, time-consuming and error-prone. The relationships between requirements and system elements are difficult to assess since the information is spread across several documents and created at different time periods in the system life cycle. Table 1 explains the difference between the 2 system engineering approaches.

S.No.	Document - Based Approach	Model - Based Approach
1.	No database to link common related items	Database tracks elements and relationships
2.	Configuration Management is very difficult	Configuration Management change impact easier to assess
3.	Any slight changes ripple through documents	Diagrams, reports, artifacts automated. Can incorporate external models, compatible with analysis models
4.	Exponential increase in timeline to develop documents	Decreases architect timeline

Table 1. The differences between Paper-based approach and Model-based approach

To better communicate, trace requirements and establish a relationship for decision-making in matching two components from two different disciplines, a System Engineering (SE) approach is adopted. Model-Based System Engineering (MBSE) is a methodology in SE that replaces the traditional way of SE, which is a document-based approach. MBSE focuses on converting all the components in SE into a model that can be connected using various relationships. MBSE has the potential to help fast-track the research and development of interdisciplinary systems. It is a newer approach adopted by various organizations because of its versatile nature, and its ability to integrate various types of systems. NASA in [2] reported that by using MBSE they were able to reduce the time of integration by 80%. Bayer in [3] explains using a case study, that MBSE would be useful to keep track of technological decisions during the project's lifetime. Due to the increase in the complexity and the interdisciplinary nature of projects MBSE would help ensure that knowledge and technical reasoning aren't lost as move across projects. The main misconception that is addressed in [4] is that MBSE does not replace the traditional system process but rather complements it. Shireen in [5] used MBSE to enable risk reduction in the certification for a new type of aircraft. The author used two specific requirements related to critical loss of thrust, to apply the MBSE methodology. However, [5] focuses more on how to enable a designer to think of requirements that are ill-defined for the new certification process and does not talk about the design and the innovations of MBSE. Risk reduction is useful when the requirements change as technology develops. Cappuzzo. F in [6] applies MBSE in the electrification of an ATR 42-500, by using Capella for the MBSE model and Amesim for the simulation of the system, the paper focuses on using their methodology to evaluate the degree of hybridization needed to meet the mission requirements. While the authors concluded that the bridge between MBSE and simulation was nonetheless attempted, MBSE however was not used for the process of design, integration, and design space exploration.

Based on the design process and the workflow is chosen, MBSE would be used to reflect on how certain decisions and processes are recorded and this in turn would help with making a methodology that integrates MBSE for future development.

3. Research Context

FutPrInt50 is an EU-funded collaborative research project set out to identify and develop technologies and configurations that will accelerate the entry into service of a commercial hybrid-electric aircraft in a class of up to 50 seats by 2035/40. Besides lower CO2 aviation footprint, FutPrInt50 aims also to minimize propeller noise emissions. [7]

One of the FutPrInt50 objectives[8] is to develop models to support engineering trade-offs and feasibility evaluation. For the hybrid electric aircraft, the propulsion systems need to be integrated the system contains major components like the electric engine and the propeller.

The electric engine includes, at the minimum, the motor, motor controller and gearbox, wiring for connections, and sensors. There are various types of Electric motors. For our use case, we have chosen a Permanent Magnet Synchronous Motor. Current work does not include the inverter or gearbox, but they would be incorporated at a later stage. The design of the propeller is also included, and components of the propeller such as chord length, airfoil, diameter and twist are included in the design phase.

This provides context to the work objectives, formalized in the following section.

3.1. Objectives

Our top objective: To develop a Co-Simulation Co-Design MBSE approach applied to an electric propulsion unit.

Steps that are taken to achieve this are the following:

- To integrate the design methodology for the Motor and Propeller.
- To document the work done by the integration's efforts.
- To design a methodology for the integration process.
- To trace the effect of variations in design parameters between the propeller and the electric engine on the overall weight, efficiency, and noise (our main figure of merits).
- To build a model of the aircraft linking that to the various systems.

3.2. Hypothesis
This work explores the use of MBSE to support and improve the research and development of the Electric Propulsion Unit. The questions that this paper address is the use of MBSE for the use in research and development of disruptive technologies and also the need for a connected way of doing research. This paper also explains the usage of MBSE in academia, where research, investigations and development is done in a collaborative way between 3 stakeholders. This is applied and tested in a small way so that in the future more stakeholders would be incorporated into this workflow.

This activity uses MBSE to address the issues in this way.

- MBSE can be used to document the design progress and the thought process when developing a methodology.
- MBSE is helpful when dealing with systems of different disciplines.
- MBSE can also help with the flow of requirements and also how the requirements are connected to the system's design.

The challenges are that MBSE can be intensive and requires a lot of man-hours to implement. To properly balance investment in modelling, "creative" activities must be addressed, in order to properly support and not hinder the design exploration activity.

The challenges of early concept design with multi-disciplinary teams. The motivations for looking at MBSE as an option is explained below:

- Team communication: For instance, reduce time regarding synchronization activities, by establishing common frameworks and definitions.
- Problem understanding: No misunderstanding in understanding the multi-disciplinary problem. It reduces error events due to different mental models regarding the system. Ensure that the same terminologies are used and variable names aren't confused.
- Lower development time: Due to the use of MBSE and the reduction of time in communications; development would be quicker
- Increase quality of work: MBSE would enable tracing decisions, assumptions and requirements. This also facilitates support discussions of integration into the full aircraft.

One of the key tenets regarding the application of MBSE is the proper planning for modelling, in order for it to support the design activities. This avoids the trap of over-modelling, either in deepness or extension, which accrues effort and delays.

It is also important to note that the scope of the MBSE should be clearly defined for the project else it might lead to modelling i.e., modelling for the sake of modelling. Modelling should be used to answer a question or explain a particular design or process. MBSE should also be tailored for the right cost at this stage of the development process i.e., early stage.

4. Methodology
MBSE is based on the intersection of three cornerstones: a methodology, a language and software tools (see [9−10]). Firstly, the methodology for the project needs to be chosen, then the language and finally the software. From an in-depth analysis of the various software available in the market, the author concluded that the methodology dictates the software to be used. Among the various methodologies available, a few of them are officially recognized by INCOSE as mentioned in [4]. Out of the three components mentioned, the methodology is the most important. The language should properly support the methodology and the tool will have a strong impact on the engineering workflow fluidity.

Six popular methodologies were investigated for this activity. They are listed below along with a small explanation:

(i) **The Object-Oriented Systems Engineering Method (OOSEM)**: integrates a top-down, model-based approach that uses OMG SysML to support the specification, analysis, design, and verification of systems.

(ii) **IBM Rational Telelogic Harmony SE**: Harmony SE methodology mirrors the classical "Vee" life cycle, development model. Rational Harmony for Systems Engineering is simply called Harmony.

(iii) **ViTech MBSE methodology**: In the Vitech MBSE methodology, it is stressed that a MBSE System Definition Language (SDL) is needed to manage model artifacts, which means that an agreed-upon information model in the form of a schema or ontology is necessary to manage the syntax (structure) and semantics (meaning) of the model artifacts.

(iv) **JPL State analysis**: JPL-developed methodology that leverages model- and state-based control architecture.

(v) **Object Process Methodology**: Developed by Dr Dov Dori, OPM is a generic language that integrates the system's structure and behaviour in one view by simultaneously representing structure and behaviour using a relatively small alphabet. OPM is based on three types of entities: objects, processes, and states, with objects and processes being the higher-level building blocks.

(vi) **ARCADIA method for MBSE**: It was developed by Thales between 2005 and 2010 through an iterative process involving operational architects from all the Thales business domains.

The ARCADIA methodology, modelling language and Capella tool were chosen. They provide an integrated approach to MBSE within an open-source environment with a live, friendly community. This integration was deemed favourable and simpler for the project at hand. SysML, for instance, a reference SE modelling language, has a higher learning curve and is tool and methodology agnostic, with a higher associated learning curve. This was deemed unfavourable regarding the timeline of the project.

4.1. ARCADIA

ARCADIA (Architecture Analysis & Design Integrated Approach) is a model-based engineering method for systems, hardware and software architectural design.

The Arcadia methodology can be explained as having 4 layers namely

- Operational Analysis
- Functional and non-functional analysis
- Logical Architecture
- Physical Architecture

The main focus in the use case will be devoted to the Logical Architecture level, where the definition of cross relations and interfaces with other logical blocks is established at the physical layer. The Operational and System layer (functional, non-functional analysis) will be detailed from the results of the FutPrint50 project, insofar as needed to support the specific use case of the electric propulsion unit. During the project, integration of the MBSE model with simulation tools, using Python, will be explored to further support the design process for requirements and integration verification.

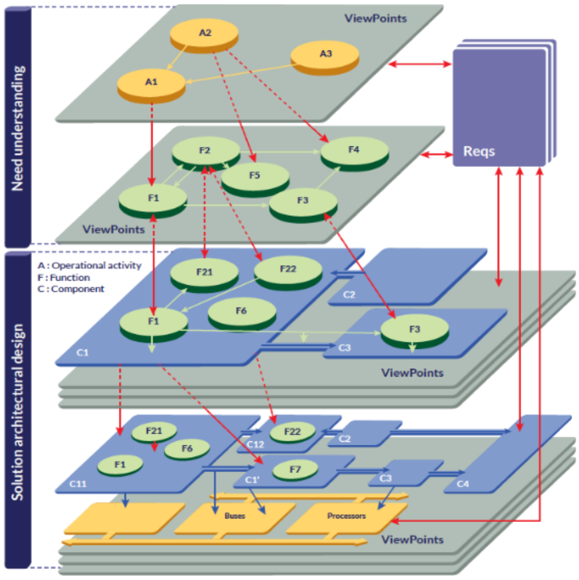

Figure 1. Arcadia methodology [10]

5. Proposed workflow

Based on these a few decisions were made for the use case. The models made are used to explain the process of designing the coupled design the technical work is explained in [cite own paper]. There are 2 models that are described here. These figures are used to describe the workflow between 3 stakeholders namely the mission designer, the motor designer and the propeller designer. However, the focus is to move towards a coupled design process. The third stakeholder or actor is called integration efforts, in this case, this responsibility was assigned to the motor designer.

The three actors involved in this process are in different parts of the world specialising in different fields. The propeller design is from TU delft from the Netherlands and the motor design mission analysis and the integration effort are done by Cranfield University in the United Kingdom. This activity uses data from different research groups, different backgrounds and different geographical locations.

Figure 2 is an operational architecture diagram this explains the people and subsystems that are involved in the integration process and how things are connected and what are the dependencies for each of the connections. The biggest connection here is shown between the motor designer and the propeller designer along with some top-level requirements and some amount of initial integration effort. This enables the designer to see the various activities involved by the various actors and the information required for an activity to occur.

Figure 3 is a Scenario diagram. This conveys the flow of information that occurs and this also explains the stage at which these data are required. It also allows the designer to either plan to have the work done sooner or to optimise this process for future work.

This also makes the possibility that when a newer method or process is developed or evolved this can add here for traceability. Hence this would ensure that the model is archived for future use or development. This is vital as it helps for quicker knowledge transfer and also enables future work to be coherent with past work.

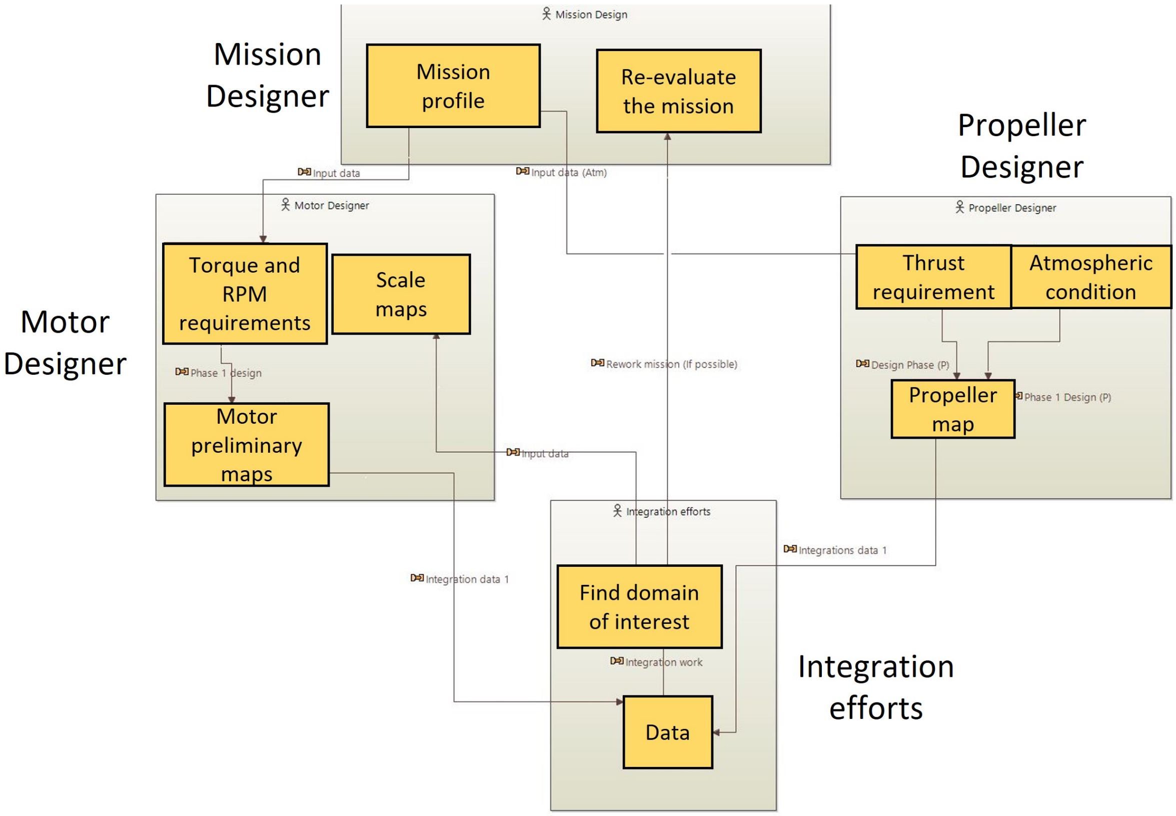

Figure 2. Operational Architecture Diagram

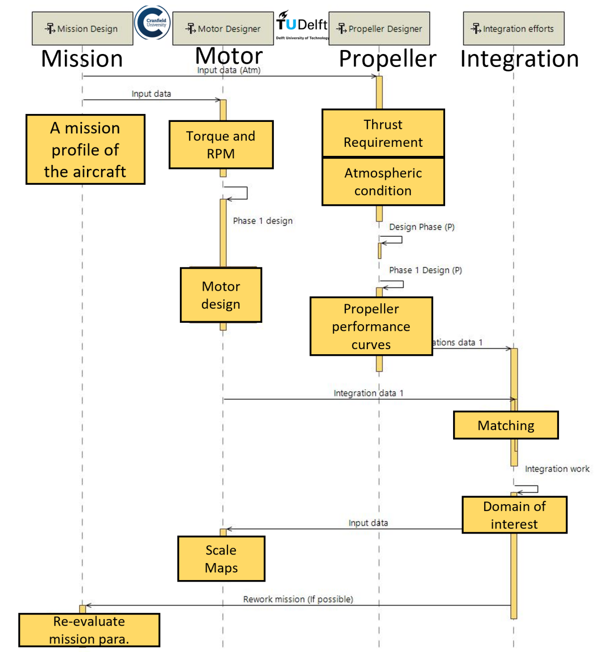

Figure 3. Scenario diagram

6. Final discussion and future development

Some preliminary insights and remarks can be made:

- **MBSE as Information HUB**: when dealing with different disciplinary approaches for integrating a system, MBSE does provide a shared understanding for integration regarding the different system components.
- **Effort:** MBSE frontloads the development. As such planning for modelling must be made. Modelling must also be clearly driven by the need to support development and research questions.
- **Requirements traceability:** Requirement connections within the models help for easier and faster validation. As the models are connected to requirements, validation happens side by side with the development of the project and so that time in the end for validating the entire system.

Follow-up activities are as follows:

- Future work would entail a workflow for integration to visualise how various design parameters affect the aircraft. Develop the requirement validation process supported by MBSE.
- Develop the MBSE aircraft and systems diagrams (logical, physical layer) to support the ongoing development activities.
- Develop a method by which time constraints could be incorporated in the design and development phase.
- To assess workflow quality and fluidity through the detection of quality events (errors, needs for synchronisation, misunderstandings) and interviews.
- When using MBSE to model such an effort, it would become a system of systems modelling effort. And when doing a system of systems modelling, the connections between various architectural components and the design workflow can be beneficial in identifying the dependent teams that would need to work together and the effect these technical teams would have on each other.

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References

[1] INCOSE SE Vision 2020, INCOSE-TP-2004-004-02.
[2] Knizhnik, J. MBSE to MIAMI to Implementation, an Overview NESC Academy Online. https://nescacademy.nasa.gov/video. Accessed Jun. 20, 2022.
[3] Bayer, T. 2018 "Is MBSE Helping? Measuring Value on Europa Clipper." *IEEE Aerospace conference.*
[4] What Is Model-Based Systems Engineering? 2020.
[5] Datta, S.*et al* 2022 MBSE-Enabled Risk Reduction for Certification of Novel Aircraft Configurations
[6] Cappuzzo, F. *et al* 2020 Application Of Model Based Systems Engineering For The Conceptual Design Of A Hybrid-Electric Atr 42-500: From System Architecting To System Simulation.
[7] Project Overview - FutPrInt50 https://futprint50.eu/about/project-overview, 2022, Accessed on Dec 19, 2022
[8] Objectives - FutPrInt50. https://futprint50.eu/about/objectives. Accessed Jun. 22, 2022.
[9] Basnet, S., *et al* 2020 "A Decision-Making Framework for Selecting an MBSE Language–A Case Study to Ship Pilotage _ Elsevier Enhanced Reader." *Expert Systems with Application.*
[10] Arcadia at a glance https://www.eclipse.org/capella/arcadia.html Accessed on Dec. 15 2022
[11] A Kiran *et al.* 2023 The Impact of Electric Machine and Propeller Coupling Design on Electrified Aircraft Noise and Performance, *SciTech Conference 2023*

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