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Model-Based Systems Engineering Capabilities to Connect Descriptive and Analytic Model: Case Studies Hybrid Propulsion of Electric Aircraft

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Abstract

Model-based Systems Engineering (MBSE) is a system development framework that utilizes the formalization of modeling to support systems engineering processes beginning early in the system development stage. This research aim is to explore and evaluate the implementation of the MBSE tool chain, especially in descriptive-analytic capabilities, traceability, ease of design customizations, and ease of making changes. MBSE processes, including requirements definition, functional decomposition, physical decomposition (architecture), and analysis were performed using a case study. The case study is the design and analysis of several hybrid propulsion configurations for electric aircraft. The ease of change and modification is shown by the process of adding, removing, and rerouting system elements and connections to modify from one configuration to another. Analysis has been performed by modeling the analysis context via the SysML Block Diagram, the interconnection of value via the SysML Parametric Diagram, and the calculation and results via the Cameo Instance Table. The result of the proposed propulsion model in SysML for full electric configuration has similar results to reference, while the results for hybrid propulsion have similar trends compared to other studies without MBSE. The method to compare analysis results and requirements with Measure of Performances (MoPs) as mediators has been proposed and performed.

Keywords: *Model-based Systems Engineering; Electric Aircraft; Hybrid Propulsion; Descriptive-Analytic Modelling.*

1. Introduction

In the face of increasing system complexity, Model-based Systems Engineering (MBSE) has started to be studied and implemented in the context of academia, industry, and government (Henderson & Salado, 2021). The International Council of Systems Engineering (INCOSE) defines MBSE as the formalized application of modeling to support Systems Engineering processes during the system life cycle (INCOSE, 2015). Study shows that there is a trend of increasing publications related to MBSE (Ma et al., 2022). Aspects of MBSE being studied include methodologies (processes and methods) (Estefan, 2008; Kranabitl et al., 2021), as well as MBSE tool-chain (Lu et al., 2018). MBSE as a framework itself is still in early development (Madni & Sievers, 2018).

The potential benefits of implementing MBSE, such as better traceability and ease of making change, have been identified by Henderson and Salado (Henderson & Salado, 2021). Beery (Beery, 2016) mentioned the potential benefits of MBSE to connect descriptive models with analytic models. Madni & Purohit (Madni & Purohit, 2019) conclude that MBSE will have a greater impact if implemented on domains with high system complexity, high environmental complexity, and long system lifespan such as transportation, aerospace, and defense. However, the study by Henderson (Henderson & Salado, 2021) also reveals that there are lack of publicly available and scientifically scrutinized comprehensive and diverse evidence of the implementations of MBSE, and its potential benefits. Further study by Henderson (Henderson et al., 2022) shows that only a fraction of potential benefits have been proven via a scientifically scrutinized approach.

A previous study by author (Zulkarnain, 2021), shows that there are several SE frameworks with each having differences in scope and focus (Zulkarnain, 2021). The framework studied includes frameworks developed by INCOSE [2] and NASA (NASA, 2007). A generic SE process is proposed in a previous study to better understand and compare different SE frameworks (Zulkarnain, 2021). There are also several other MBSE-specific methodologies developed and proposed such as (Beery, 2016; Estefan, 2008; Kranabitl et al., 2021). Compared to the SE framework, the MBSE framework typically has a more specialized but narrower scope emphasizing the integration or usage of modeling tools. However, the general processes are very similar to the generic SE processes.

SysML is the most used language in the context of the MBSE tool-chain (Ma et al., 2022). SysML is a general-purpose graphical modeling language that supports the analysis, specification, design, verification, and validation of complex systems (Friedenthal et al., 2008). A SysML model consists of model elements (metaclass) that represent structural elements, requirements, behaviors, design rationale, and their interrelationships. Cameo System Modeler (further called Cameo) is the most used MBSE tool that implements SysML (Ma et al., 2022). While MBSE tools sometimes need to be connected to other analytic tools to provide analysis capabilities such as (Beery, 2016) and (Duncan & Etienne-Cummings, 2019), Cameo has limited analysis capabilities due to having a parametric engine (Cameo Systems Modeler - CATIA - Dassault Systèmes®). Modification of SysML for specific use is possible, such as done by (Boggero et al., 2021) introducing "needs" and "derived constraints" which are a specialization (a Stereotype) of the SysML (metaclass) "requirements". Thus, SysML and Cameo will be used in this study.

Advanced Air Mobility (AAM), is an air transportation system that moves people and cargo between places previously not served or underserved by aviation – local, regional, intraregional, and urban – using revolutionary new aircraft that are only just now becoming possible (NASA, 2021). Hybrid propulsion is one of the "revolutionary technologies" which can be integrated into AAM (Straubinger et al., 2020). Hybrid propulsion appears as the most viable solution for an energy-efficient, cleaner, and quieter aeronautical propulsion since it can combine the advantages of the conventional propulsion system and the all-electric approach (Rendón et al., 2021). There are several configurations of hybrid propulsion, such as serial, parallel, and serial-parallel (D. F. Finger et al., 2020; Rendón et al., 2021; Schömann, 2014). However, the current methods of analysis are typically very configuration-specific.

This research aim is to explore and evaluate the implementation of the MBSE toolchain, especially in descriptive-analytic capabilities, traceability, ease of design customizations, and ease of making changes. An MBSE process, including requirements definition, functional decomposition, and physical decomposition (architecture), and analysis are performed using a case study. The case study is the design and analysis of several aircraft hybrid propulsion configurations. Changes and modifications are simulated by changing the value in the requirements and changing the architecture of the hybrid propulsion. A more generic method to model hybrid propulsion by using a block diagram is proposed in this study. A method to structurally evaluate the results of analysis to requirements is also proposed in this study.2.

2. Methodology

2.1. Model-based Systems Engineering Processes

In this study, a simplification of SE processes, modified from reference (Zulkarnain, 2021), is used as MBSE process. The processes are as follows:

- *Requirements definition*. Requirements can be modeled as a requirements table and/or requirements hierarchy diagram.
- *Logical decomposition* – allocation of requirements to functions. Functions can be modeled as a functional flow diagram, state machine diagram, sequence diagram, and/or functional breakdown diagram. Traceability between the functions and requirements is also developed in this process.
- *Logical decomposition* – allocate functions to architectural elements. Architectural elements can be modeled as a hierarchical diagram and an interrelationship diagram. Traceability between the architectural elements to functions and requirements is also developed in this process.

- *Design definition* – define the specification of architectural elements. Specification tables
- *System analysis* – perform analysis of the developed design. specific tools are used to model and perform analysis
- *Verification* – compare analysis results to requirements.

2.2. MBSE Tool Chain

The MBSE toolchain is a set of software(s) or tool(s) to support MBSE processes. Each set has a tool(s) associated with at least four tool-chain functions identified by Ma (Ma et al., 2022), which include requirement management, system modeling, system analysis, and data integration. Multiple modeling tools may be needed to fulfill all functions. The following are definitions used in this study:

- *Descriptive model* includes the requirements diagram, system hierarchy model, interrelationship/interconnection model, and behavioral model (Beery, 2016; Duncan & Etienne-Cummings, 2019; INCOSE, 2015). In (Specking et al., 2018), the list of variables (for example aspect ratio of UAV wing) and list of constraints (list of equations) are defined as descriptive.
- *Analytic model* includes quantitative relationships such as mathematical equations. The most important aspect of the analytic model (or analytic modeling tools) is the ability to compute or yield numerical results via the calculation thread (Beery, 2016; Duncan & Etienne-Cummings, 2019; INCOSE, 2015; Specking et al., 2018).
- *Descriptive-analytic connection* connects structural model(s) as an input for the calculation thread and either directly updates or shows possible updates for the structural model as an output. Its use of architecture to support analysis (and vice versa) ensures that behaviors represented in the models and simulations created in the System Analysis Domain can be traced to functions prescribed in the System Architecture Domain. Similarly, it ensures that the system configurations and performance standards established in the physical architecture are consistent with the systems and system components created in any external models and simulations (Beery, 2016).

SysML is used as the MBSE modelling language with Cameo Systems Modeller chosen as the MBSE tool-chain in this study. SysML used visual diagrams as viewpoints to represent the MBSE processes. The diagram in this study includes:

- *SysML requirements diagrams*. Shows requirements as a structural/hierarchical model. This diagram represents the requirements definition process.
- *SysML behaviour diagrams*. Shows the behavior or functions either represented as use case, activity, signal/trigger sequence, or state. The diagram can be a functional flow diagram, a state diagram, a use case diagram, or a sequence diagram. This represents the logical decomposition process.
- *SysML system structure block definition diagram*. Shows the structure/hierarchy in a system. This represents the logical decomposition and design definition process.
- *SysML system structure internal block diagram*. Shows the relationship between the system's structural elements. This represents the logical decomposition and design definition process.
- *SysML requirements traceability diagram*. Shows the relationship between requirements, behavior, and structures. This represents the traceability processes that happen throughout the. This diagram can also be used to shows the verification process.
- *SysML analysis context block definition diagram*. This represents the structure system analysis process, what equations will be used, and what structural parts of the system will be involved.
- *SysML analysis context parametric diagram*. This represents the detail of the system analysis process. The relationship between the parameters in the equation and system structure. The equation is modeled as SysML constraint. This diagram is the bridge between the descriptive model and analytic models, as it represents the data flow and equation that can be executed by analytic models/engines.

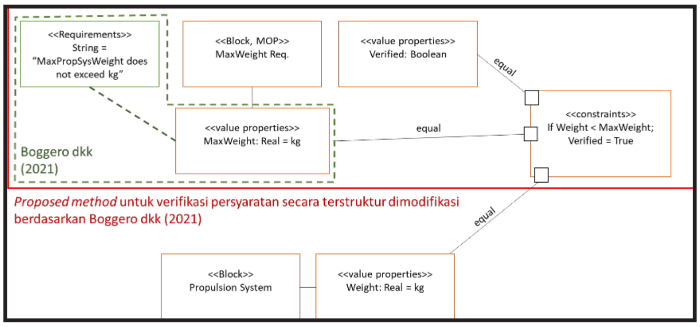


Figure 2-1: Schematic of proposed SysML verification method.

The verification process includes comparing the results of the analysis to requirements. However, SysML stores requirements text as a "string" data type, and thus cannot be directly compared to the value of analysis results. Boggero proposes modified SysML requirements to store values (Boggero et al., 2021), however, the study does not discussed how those value can be compared. In this study, we propose a way to store values and compare values. The requirements are connected to a modified SysML block, called MOP (means of performance). This is inspired by MoP in NASA SE which store system performance that is observed and compared to analysis results throughout the SE processes (NASA, 2007). The block stores the requirements value and also a boolean which shows whether the requirement is fulfilled or not. A constraint is made to store comparison logic between MOP and analysis results. The schematic of the proposed method is shown in Figure 2-1.

2.3. Case Studies

The case study is hybrid propulsion for an electric aircraft. The electric aircraft used as case study is full electric Lange Antares, as it is one of the proven small electric aircraft with enough information for this case study. The baseline information was obtained from the reference (Hepperle, 2012), with several values either assumed or recalculated using the proposed method which will be discussed further in this Subpart. A modified hybrid propulsion configuration is designed and analyzed based on the mission profile of Lange Antares, to simulate design modification. A change in the mission requirement will be performed to simulate change.

The hybrid propulsion system requirements are derived from the aircraft system and mission requirements. To simplify the case study, the mission requirements are the endurance of the aircraft and the height at which it performs its mission. The reserve time is not defined in this study. To fulfill this requirement, the hybrid propulsion must be able to provide power and energy to perform the mission. To introduce a constraint, the maximum propulsion requirement is also defined. To simulate change, there are two sets of requirements, the initial requirements, and the final requirements, which have different values. The list of requirements is shown in Table 2-1. The changed values are marked with bold font.

Table 2-1: Set of requirements in this study

Set of Req.	Initial Requirement	Final Requirement
Mission requirements	The aircraft have endurance of 1.3 hours at altitude of 5000 m above sea level and airspeed of 25 m/s	The aircraft have endurance of **1.5** hours at altitude of 5000 m above sea level and airspeed of 25 m/s
Mission requirements	The aircraft has rate of climb of at least 5 m/s.	The aircraft has rate of climb of at least **6** m/s.
System requirements	The aircraft maximum weight does not exceed 530 kg.	The aircraft maximum weight does not exceed 530 kg.
Propulsion system requirements	The hybrid propulsion system must be able to provide power and energy to perform mission	The hybrid propulsion system must be able to provide power and energy to perform mission
Propulsion system requirements	Total weight of propulsion system must not exceed 100 kg.	Total weight of propulsion system must not exceed **120** kg.

The aircraft mission profile and as well as several assumptions of system specification is required to calculate the required maximum power and total energy. The flight segment is assumed to be climb and cruise only. The initial and final value of mission and aircraft parameters/specifications is defined and shown in Table 2-2. The parameter is assumed to be constant throughout the segment.

Table 2-2: Assumption of mission and aircraft specifications

Mission/Aircraft Parameter	**Climb** **Initial / final**	**Cruise**
Flight Duration, hours	0.33 / 0.33	0.97 / 1.27
Flight speed, m/s	25 / 25	25 / 25
Rate of climb, m/s	5 / 5	0 / 0
Aircraft LD ratio	30 / 30	43 / 43
MTOW, kg	530	530

The required power (P_{req}), in kW, that needs to be provided by the hybrid propulsion at each segment provided by the modified equation from the reference (Ruijgrok, 2009) are provided in equation (2-1).

$$P_{req} = W \times \left(\frac{L}{D}\right)^{-1} \times V + W \times RoC \tag{2-1}$$

Then, the required energy (E_{req}), in kWh, at each segment can be calculated by multiplying the required power obtained from equation (2-1) with the flight duration (t), as shown in equation (2-2).

$$E_{req} = P_{req}\, t \tag{2-2}$$

Schömann (Schömann, 2014) categorizes the elements of a propulsion system into three: energy sources (such as battery and fuel); power converter (such as electric motor and internal combustion engine); and thrust generator (such as propeller). Each propulsion element will be modeled as a block (Figure 2-2), with the input of power (or energy), the output of power (or energy), and efficiency, with the equation as follows.

$$P_{out} = P_{in} \times \eta \tag{2-3}$$

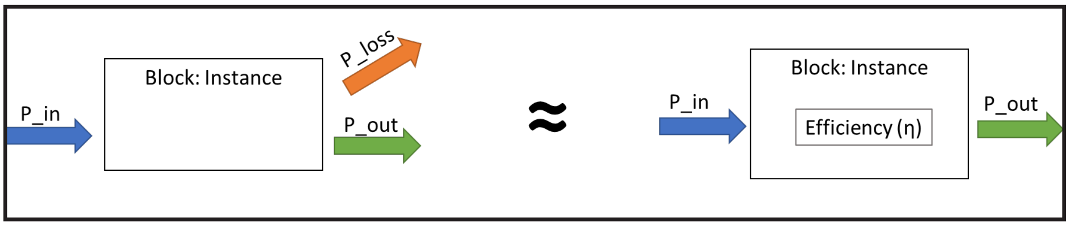


Figure 2-2: Block modelling of propulsion system element

By using this method, we can calculate the required P_{out} for each propulsion element at each flight segment. The energy required in each segment for energy storage can then be calculated by multiplying the Pout (or dE/dt) with the segment duration. The total energy required (E_{total}) for energy storage is the sum of each segment energy required. With known P_{out} or E_{total} for each, the weight of each propulsion element can be calculated if the energy density or power density of the propulsion element is known.

For this study, the efficiency, energy density, and power density is assumed from other sources. The efficiency of the energy converter can also be calculated, by using equation (2-3), with mechanical power (torque times rpm) as Pout. The pin is different for electrical power (voltage times current) and internal combustion engine (fuel flow times fuel energy density). Data for internal combustion engines was obtained from reference (Brown, 2015; Rittenhouse, 2014). For electric motors, several T-motor data are collected (T-MOTOR). An electric generator is assumed to have the same efficiency and power density as an electric motor. As the MTOW is assumed to be constant, the P_{req} will be the same for all configurations, thus the propeller sizing and weight should be the same. Thus, the weight of the propeller can be ignored for comparison's sake. Table 2-3 reviews the specifications of propulsion elements.

Table 2-3: Propulsion elements specifications.

VALUE	BATTERY	FUEL	ELECTRIC MOTOR	ELECTRIC GENERATOR	INTERNAL COMBUSTION ENGINE	PROPELLER
Type	Electric power and energy source	Chemical power and energy source	Electric to mechanical converter	Mechanical to electric converter	Chemical to mechanical converter	Mechanical to thrust converter
Efficiency	-	-	75-90% (calculated from (T-MOTOR, n.d.))	75-90% (same as electric motor)	20-35% (Brown, 2015; Rittenhouse, 2014)	80% (Hepperle, 2012)
Energy Density, kWh/kg	0.25 (Hepperle, 2012)	10 (Kerosene) (Hepperle, 2012)	-	-	-	-
Power Density, kW/kg	-	-	1.3 (Lange Antares Motor) (EASA, 2014)		2 (Hepperle, 2012)	-

Three cases of propulsion system architecture (as shown in Figure 2-3) is chosen for this study: full electric (case 1), serial hybrid (Case 2), and serial-parallel hybrid (Case 3). The three cases are chosen to simulate modification or change in system development. The system is modeled as Case 1 first, and then changed to Case 2, then to Case 3.

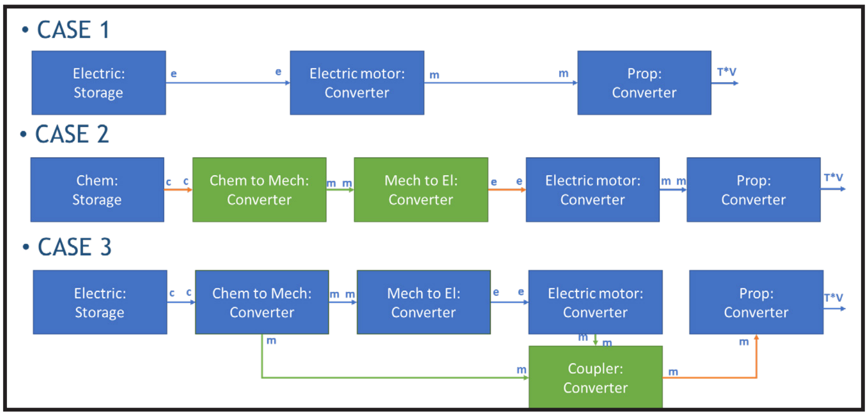


Figure 2-3: Three propulsion system architectures in this study

3. RESULTS AND DISCUSSION

3.1. Requirement Definition

The requirement is modeled as a hierarchical/structural model as shown in Figure 3-1. An example of the relationship between requirements and their respective MOPs is shown in Figure 3-2. However, instead of writing the value in requirement.text such as "Max propulsion system weight does not exceed 100 kg" such as in Figure 3-2a, it is written as "Max propulsion system weight does not exceed MOP.MaxPropSysWeight" such as in Figure 3-2b. The value of endurance is instead only stored in the minEndurance MOP. If there is a change in the endurance value, instead of both requirements and MOP is going to be changed, the change is instead performed in the MOP only, as shown in Figure 3-2c, which can increase modeling consistency.

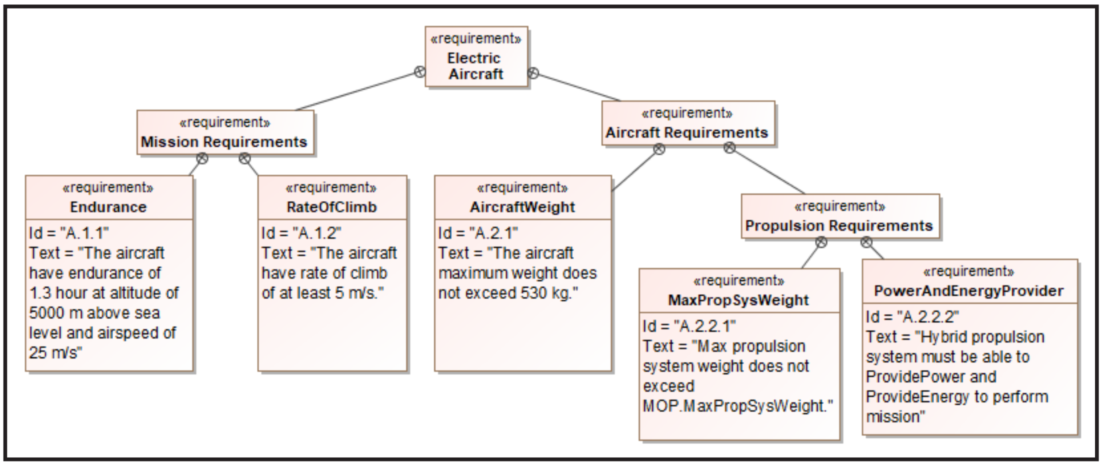
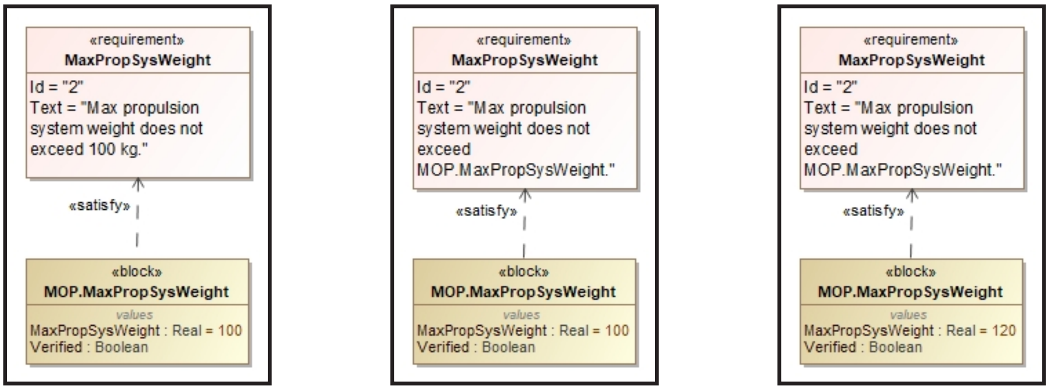


Figure 3-1: Requirements model



(a) (b) (c)

Figure 3-2: Requirement and MOP relationship with value written on both requirement and MOP (a), with value written only on the MOP (b), and changing value from 100 to 120 only on MOP (c).

3.2. Logical Decomposition

Initially, the aircraft mission profile is modeled as a functional flow diagram using the SysML activity diagram, as shown in Figure 3-3a. The typical mission profile consists of several flight segments, including takeoff, climb, cruise, descent, alternate, and landing. However, SysML activity is not typically used to store the values of each segment, such as aircraft speed and altitude. Thus, the mission profile and the flight segment are also modelled as block, as shown in Figure 3-3b. The SysML association connects mission profile activity and block, as shown in Figure 3-3c.

The propulsion system functional breakdown structure can either be modelled as either SysML use case, SysML activity, or SysML block. Both use case and activity typically represent function, with use case typically representing high-level functions, and activity representing time or sequence-related functions. Block may be used if the function requires storing value. Modelling function as use case is also still appropriate for this case compared to the other two alternatives. This is due to how functions were typically made as a use case early in the MBSE processes. Activity and block diagrams were typically made when more detailed representations were needed. These alternatives are shown in Figure 3-4.

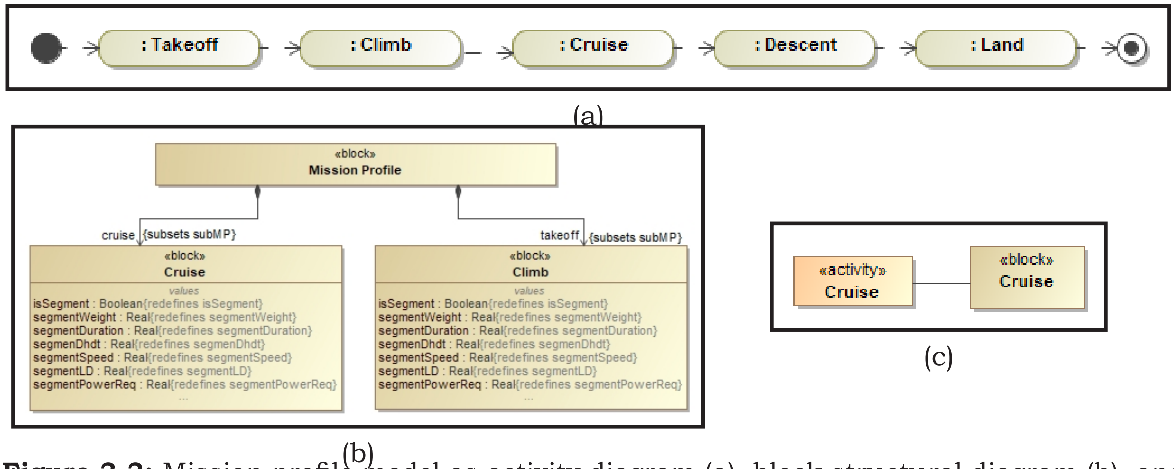


Figure 3-3: Mission profile model as activity diagram (a), block structural diagram (b), and relationship between activity and block (c).

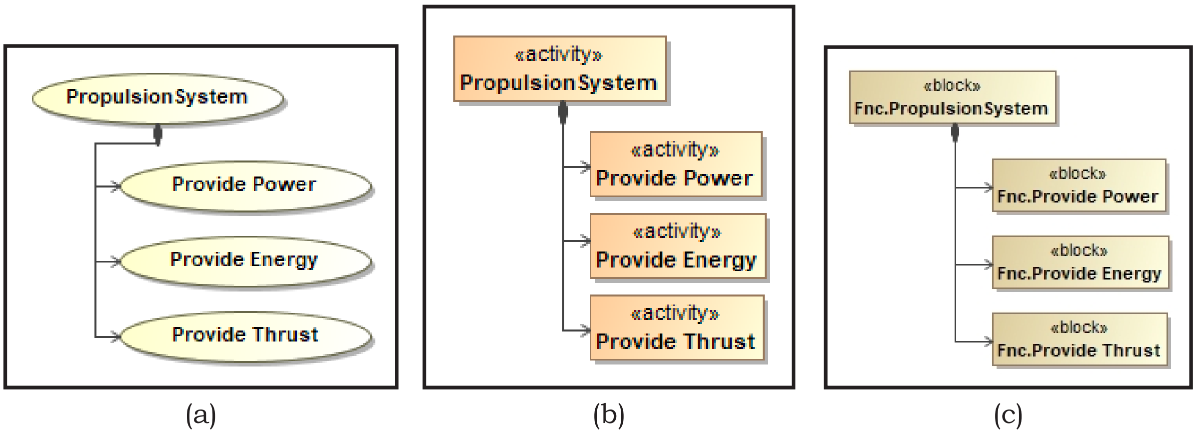


Figure 3-4: Functional breakdown structure using use case (a), activity (b), and block (c).

The "hardware" of the propulsion system itself is represented by two diagrams. The structural breakdown is modelled as a SysML Block Definition Diagram and the architecture is modelled as SysML Internal Block Diagram. Figure 3-5 shows the model of the three cases. The ease of change and modification can be observed by how each case can be modified to other cases by adding/removing block and adding/removing/rerouting connections.

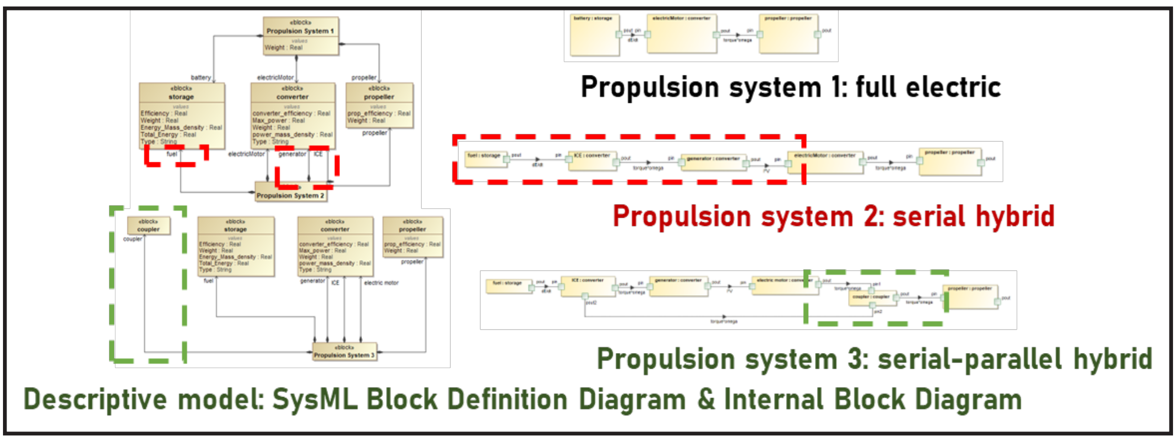


Figure 3-5: Propulsion structure for CASE 1, CASE 2, and CASE 3.

3.3. Descriptive-Analytic Connection

The first step to model descriptive-analytic connection is by defining the context of analysis using the SysML Block Definition Diagram. This diagram consists of the structure (SysML block) and equation (SysML constraint) required to perform the analysis. An example for CASE 3 is shown in Figure 3-6. It consists of a FlightSegment <<block-Pattern>>, one sumEnergy constraints, three findMaxPower constraint for each energy converter, a segmentPreqCalc constraint to calculate, and it also refer to the propulsion system structure. The <<Pattern>> means it is capable to refer to its child block. In this example, the analysis will calculate energy and power required for Cruise and Climb (child) FlightSegment, and then calculate the total energy and max power at Mission Profile (parent) FlightSegment.

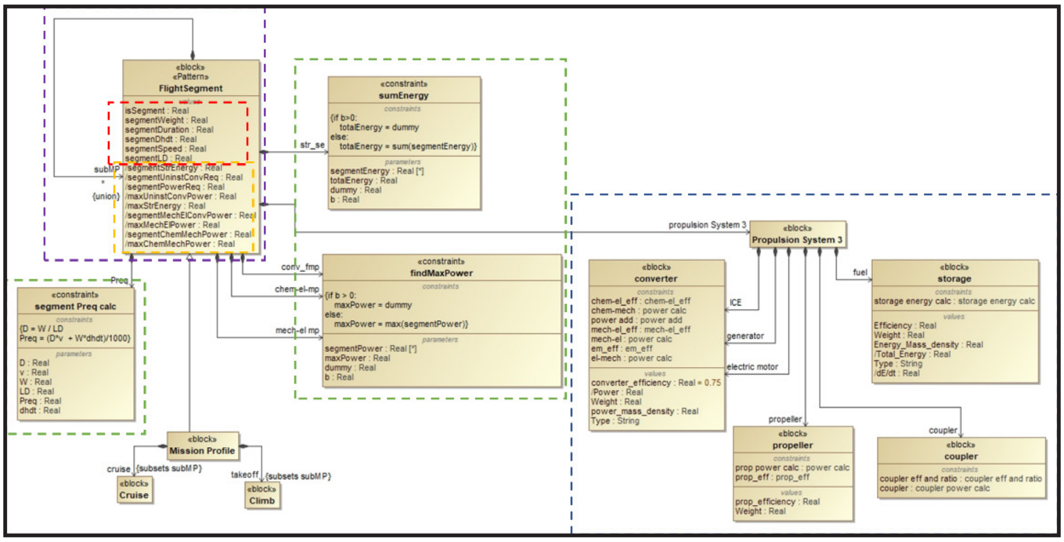


Figure 3-6: Analysis context for CASE 3.

The next step is to define the connection between values (Block) or parameters (Constraint), using SysML Parametric Diagram. The results of the analysis is not stored in the Block Values or Constraint Parameter, but instead stored in an element called *Instance*. Cameo used an instance table to display the results of calculation, shown in Figure 3-8. As in previous discussion, change and modification can easily be performed by adding, removing, and rerouting system elements and connections.

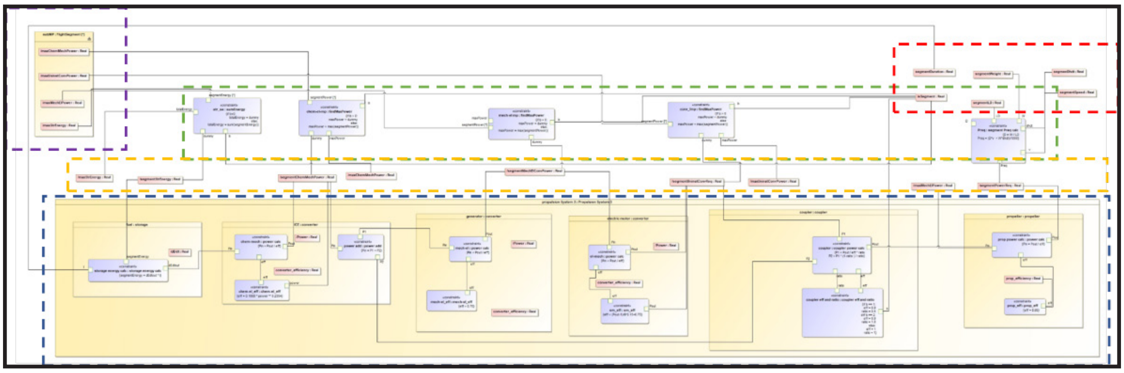


Figure 3-7: Parametric diagram for CASE 3.

Criteria

Classifier: FlightSegment | Scope (optional): mission Profile : Mission Profile | Filter:

#	Name	isSegment : Real	segmentWeight : Real	segmentDuratio : Real	segmenDhdt : Real	segmentSpeed : Real	segmentLD : Real	segmentPowerR : Real	segmentUnins : Re	maxUninstConv : Real	maxMechElPow : Real	segmentMechEl : Rea	segmentChemM : Rea	segmentStrEner : Real	maxStrEnergy : Real
1	mission Profile	0	5300	0	0	0	1	0	0	20.7843	0	0	0	NaN	108.425
2	mission Profile.takeoff	1	5300	0.33	5	30	30	31.8	20.7843	20.7843	37.4118	19.2494	46.4502	61.6073	61.6073
3	mission Profile.cruise	1	5300	0.97	0	30	43	3.6977	4.8336	4.8336	4.3502	5.9388	7.9184	46.8177	46.8177

Figure 3-8: Results of analysis using Cameo Instance Table.

3.4. Results of Analysis

The method used cannot only calculate the total but also each specific structural element. As shown in Table 3-1, CASE 1 calculation results are close to baseline results from (Hepperle, 2012) and (EASA, 2014). However, the calculation used a Lange Antares engine which has a power density of 1.3 kW/kg electric motor (EASA, 2014), the modern electric motor can have a power density of 2 to 6 kW/kg (Hepperle, 2012). From this calculation, CASE 3 – serial-hybrid propulsion has a lower total weight compared to CASE 1 and CASE 2. Furthermore, when the target endurance is increased (after change) from 1.3 hours to 1.6 hours, CASE 3 still has a lower total weight. This is due to the split of power between the EM and ICE. Even though CASE 3 has lower total efficiency due to introducing COUPLER, the split of power reduces the required available power for the EM and ICE, thus reducing total weight. CASE 1 has a lower weight than CASE 2 when the endurance is 1.3 hours but is higher when the endurance is 1.6 hours. The comparison before and after the change is shown in Table 3-2. These results, especially at higher endurance, are similar to research done by Finger (D. F. Finger et al., 2020), in that the full electric configuration has the highest weight.

Table 3-1: Propulsion elements weight results.

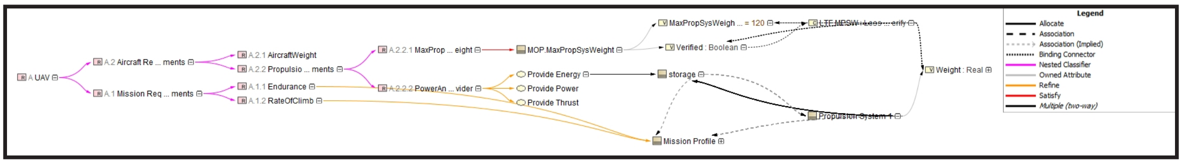
CASE/REFERENCE	Energy Converter Weight	Energy Storage Weight	Total Propulsion System Weight
Full electric (Hepperle, 2012)	-	80 kg (battery)	109.2 kg
Lange Antares TCDS (EASA, 2014)	29.2 kg (EM)	-	
CASE 1	29.1 kg (EM)	80.1 kg (battery)	109.2 kg
CASE 2	29.1 kg (EM), 36.3 kg (GEN), 39.0 kg (ICE)	9.63 kg (fuel)	114 kg
CASE 3	16.1 kg (EM), 20.2 kg (GEN), 33.3 kg (ICE), 15 kg (COUPLER)	9.18 kg (fuel)	93.8 kg

Table 3-2: Propulsion weight before and after requirement change.

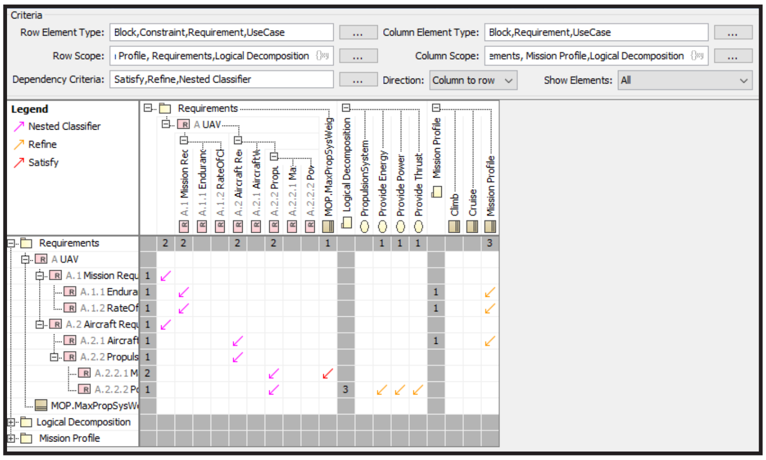
CASE	Before Req. Change (1.3 hr minEndurance)	After Req. Change (1.6 hr minEndurance)
CASE 1	109.2 kg	116.9 kg
CASE 2	114 kg	115.2 kg
CASE 3	93.8 kg	95.1 kg

3.5. Traceability in SysML

The traceability in SysML is stored and defined as connections. Cameo is not only capable of storing direct connections but also implied connections. There are two possible visualizations provided by Cameo, relationship map and dependency matrix. For the example in Figure 3-9a, Requirements A.2.2.1 MaxPropWeight and its MOP have implied connections to the functions and structural elements allocated by the requirements A.2.2.2 PowerAndEnergyProvider and mission profile defined by A.1.1, A.1.2, and A.2.2. A similar relationship, between requirements, use cases (functions), MOP, and mission profile is shown using dependency matrix in Figure 3-9b. In this case, a relationship map provides a more intuitive understanding by visualizing the networks of system elements, while a dependency matrix provides the ability to analyze completeness. Furthermore, exploration of both shows that dependency matrix has better ability to visualize high number of system elements, while a relationship map has a better ability to visualize specific connections. As an example, the indirect relationship between the rate of climb requirement with weight value can easily be identified by using the relationship map instead of the dependency matrix. However, the completeness, in this case answering the question "Have all requirements have been connected to other elements which satisfy/refine/elaborate that requirement?" can easily be analyzed using a dependency matrix, by checking does the dependency matrix most left column all has number which indicates the number of directly connected element. However, the correctness of the connection still needs to be checked and analyzed manually.



(a)



(b)

Figure 3-9: Traceability diagram using relationship map (a) and dependency matrix (b).

3.6. Requirement Verification

Similar to the descriptive-analytic connection, the requirements verification needs to be defined in two diagrams, the descriptive context, and the parametric diagram. The descriptive context contains the MOP (and its requirement), the structural block, and the comparison constraint as shown in Figure 3-10a. For this example, the requirement verified is MaxPropSysWeight, the MOP is MaxPropSysWeight, and the block is the Propulsion System The constraint needed is LessThanVerify, thus when the weight value of the propulsion system is not less than the MaxPropSysWeight MOP, the requirement is not verified for the configuration. The results, in Figure, only CASE 3 fulfill the requirement. After the MaxPropSysWeight changed from 100 to 120 kg, all CASEs fulfill requirement.

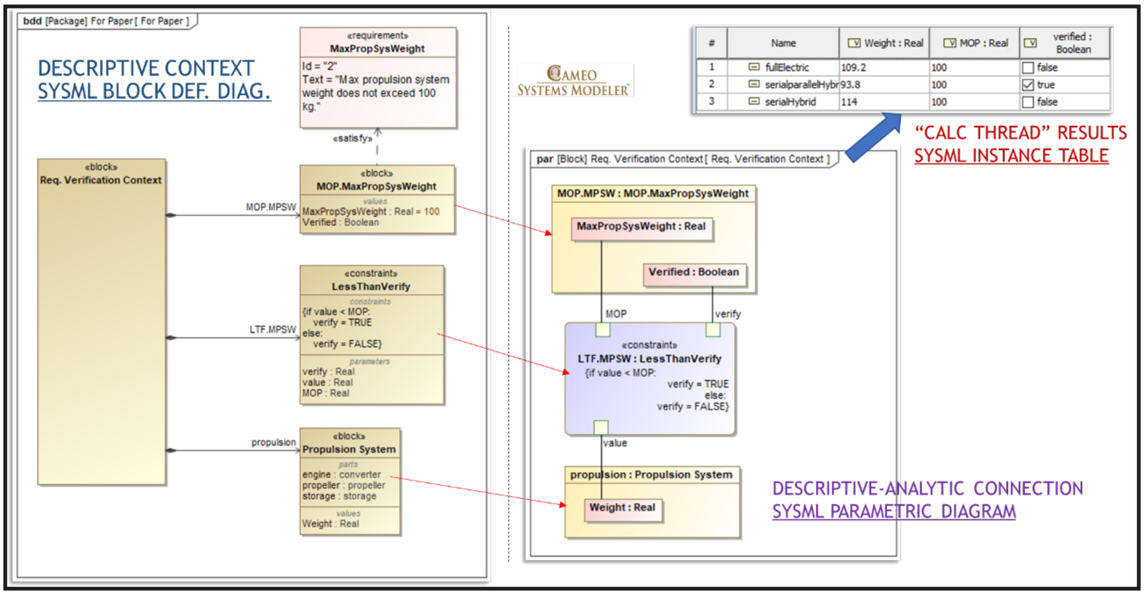


Figure 3-10: Requirement verification modelling in SysML.

4. CONCLUSION

In this paper, a generic MBSE process has been proposed and performed, using SysML modeling language and Cameo System Modeller as modeling tools. Case studies comparing several hybrid-electric configurations are performed. The results of the proposed propulsion model in SysML for full electric configuration have similar results to reference, while the results for hybrid propulsion have similar trends compared to other studies without MBSE. Changes in requirements and modifications in hybrid propulsion architecture and parametric shows were conducted. The ease of change and modification is shown by adding, removing, and rerouting system elements and connections to modify from one configuration to another. Analysis has been performed by modeling the analysis context via SysML Block Diagram, the interconnection of value via SysML Parametric Diagram, and the calculation and results via the Cameo Instance Table. The method to compare analysis results and requirements with MOPs as mediators has been proposed and performed.

The author acknowledges that this paper still has limitations which need to be further studied. The modeling and analysis of each configuration are performed sequentially. Capabilities of SysML to model and analyze multiple configurations at once needs the be further studied. The configuration of propulsion is also limited to a single set of propulsion, while there are trends for distributed propulsion such studied by (D. Finger et al., 2017). Validation of MBSE using more complex case studies than the propulsion system, such as the AAM aircraft and even the AAM mission needs to be further studied. Furthermore, the capability to model and perform trade studies and optimization using SysML as a base needs to be developed and studied.

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Contributorship Statement

MFZ is the main contributor.

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