MBSE APPROACH FOR CONCEPTUAL DESIGN OF HYBRID ELECTRIC VTOL AIRCRAFT

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Abstract
In this study, it is ensured that the conceptual design cycle and sizing studies of the aircraft are carried out in accordance with customer and design requirements by using model-based systems engineering methods (MBSE). It is aimed to handle conceptual aircraft design process with MBSE approach while also creating a link between inhouse design tools and MBSE tools. Firstly, the aircraft mission profile and top-level requirements are determined based on customer requirements derived from literature survey. According to these top-level requirements and technology assessment, the aircraft design concept was decided as lift-cruise configuration. The concept design cycle is defined by the systems engineering approach. In conceptual design process, constraint analysis and sizing studies are mainly performed using inhouse design tools scripted with Matlab/Python environment. In the study, requirements analysis, functional analysis and allocation, design synthesis and requirement verification are performed, respectively. A link has been established between Cameo, which includes SysML models, and MATLAB, which includes sizing algorithms. Thanks to this link, requirements verification is created, an iterative design cycle. Verification of requirements are done with sizing results of candidate aircraft subsystems generated as a results of design synthesis. As a result of study, MBSE approach satisfies the traceability and generalization of the aircraft design process when compared to traditional design approach.

1. INTRODUCTION

As the technology has been growing, the complexity in aircraft design is also increasing because of increasing demand for new aircraft concepts. In this context, the latest emerging concept is the vehicle for the urban air mobility (UAM). This concept has been developing to take place of taxi and shuttles mainly for intracity and intercity missions in the near future. Full-electric and hybrid technologies in the UAM are developing concepts. This new concept has to be consisted of a lot of subsystems to increase the safety and the comfort of both passenger and people. These subsystems bring more challenge and complexity in the design process. To overcome this complexity, model-based system approach is promising approach in the aircraft design.

Furthermore, several essential studies have been made that constitute milestone such as market feasibility, improving safety, distributed electric propulsion [1], noise reduction, emission abatement, performance, battery usage, hybridization factor with respect to flight phase[2], accelerating the certification timetable, infrastructure, multi fidelity modeling and simulation, multidisciplinary design optimization[3,4].

There are lot of sizing studies of hybrid-electric[5,6] and electric[7,8] VTOL aircraft. There are few research using MBSE approach to conceptual design and sizing of the aircraft [9–11].

This paper aims to design the hybrid e-VTOL concept design cycle for intercity mission profiles using the Model Based Systems Engineering (MBSE) approach. Firstly, conceptual design process of aircraft is defined. Customer requirements, mission profile, design concepts and available technologies are identified to design eVTOL aircraft. Secondly, model-based system engineering approach and SysML modeling language are explained briefly. General system engineering process used in system development is identified. Finally, MBSE approach is applying to conceptual design process. Requirement analysis, functional analysis/allocation and design synthesis are performed for conceptual design of e-VTOL aircraft system. In addition, requirements are validated for candidate aircraft. Conceptual design

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process is modeled in MagicDraw No Magic software, which uses SysML language.

2. CONCEPTUAL DESIGN OF HYBRID ELECTRIC VTOL AIRCRAFT

2.1. Design Process of Aircraft

Design of an aircraft is an iterative process. This iterative design process can be represented with design wheel (Figure 1) [12]. Process begins with defining set of requirements by customer. Design concepts are developed according to requirements. Analysis of these design concepts are performed. Sizing and trade studies are performed to find the best candidate that satisfies requirements. Evaluation of requirements are check whether they are feasible or not. In addition, necessary requirements are derived along these iterations.

When this design wheel is iterating, aircraft system generally completes three major phases as conceptual design, preliminary design and detail design. Focus of this study is the conceptual design of VTOL aircraft. Conceptual design process can be explained in Figure 2 as in Ref [12]. In conceptual design phase, configuration arrangement, size and weights of components are identified. Therefore, the proposed sizing methodology given in Figure 3 will be applied for conceptual design of VTOL aircraft [13].

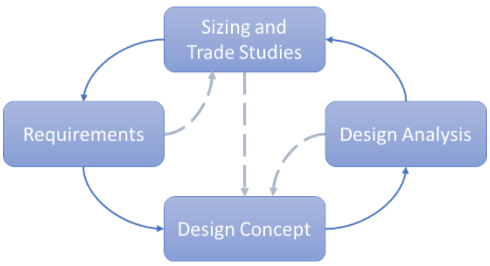

Figure 1. The design wheel [12]

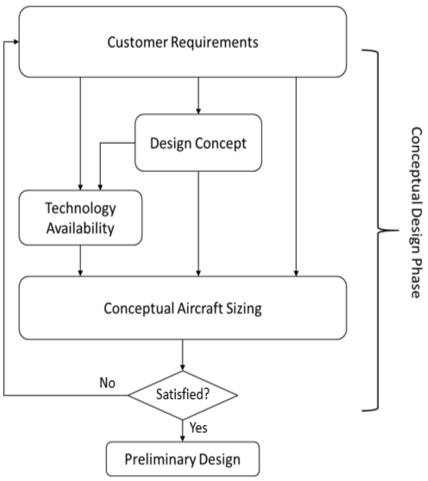

Figure 2. Conceptual Design Process

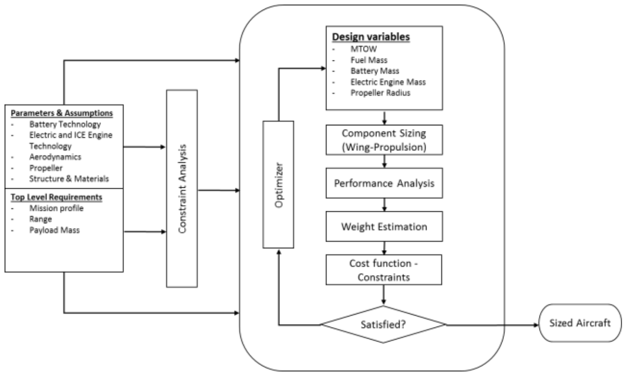

Figure 3. General scheme of sizing process [13]

2.2. Customer Requirements

As the urban air mobility becomes widespread, various mission profiles were specified for different aircrafts that have different concepts. Mission profile is given in the Table 1 are proposed and illustrated in Figure 1. The payload capacity requirement was determined due to the aircraft design regulations.

Table 1. Mission Segments

	Mission Segment	Lift-Cruise Mission Specification
1	Take-off	-
2	Vertical Climb / Hover	100 fpm ROC / 3 min
3	Transition	-
4	Climb	600 fpm ROC
5	Cruise	112 mph / 5500 ft
6	Descend	1000 fpm ROD
7	Retransition	-
8	Vertical Descend	100 fpm ROD / 3 min
9	Landing	-

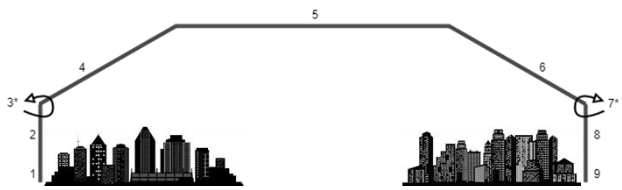

Figure 4. Mission Profile

2.2.1. Top Level Requirements

The top-level requirements such as cruise speed, range, payload must be defined in order to size the aircraft and then to analyse the performance. Mission requirements are given in previous section. The other top level requirements related to UAM studies are explained here.

The payload capacity requirement was determined due to the aircraft design regulations [14]. Considering passenger weights for different male and female ratios, different passenger capacities and different seasons in regulations, the maximum value which is 116 kg (256 lb) is accepted as payload capacity to cover the widest payload range.

The cruise speed is one of the most important parameters to identify the performance of the aircraft. To compete with the similar aircrafts, the cruise speed is selected based on similar aircrafts which are 180 km/h for winged aircraft configuration.

The mission range for intercity missions is generally changing between 100 km to 200 km [4]. In this study, mission range was defined as 100 km.

Besides, there are more requirements that are less decisive on the aircraft design but still determine some boundaries on the design phase. One of them was mentioned in the references [3][15] that is a small footprint which should be lower than 50 ft. for landing and parking. Another important requirement is the number of the propeller in the vertical direction. For the redundancy, there should be at least 6 propellers in the vertical direction in order to accommodate a loss of one motor or propeller [3]. Also, there should be a safe transition from hover to cruise or vice versa [3].

2.3. Design Concepts & Subsystem Technology Assessment

In this study, design concepts and available technologies were considered. Lift & cruise configurations is chosen due to simplicity compared to other configurations. The lift & cruise configuration consists of total of 9 rotors which are 1 pusher (for forward flight) and 8 vertical rotors (for vertical flight). Moreover, V-shape tail is supported by boom mounted below the wing.

In hybrid technology, the three configurations are mainly utilized such as series-hybrid, parallel hybrid and series-parallel designs. When all configurations are considered, it is seen that mechanical power transmission from both power sources to vertical propulsors need complex design. Therefore, serial hybrid is preferred as hybrid electric configuration in this study [5]. To avoid dramatical increasing of the battery weight in long range mission, the hybrid ratio of the hybrid system was decided to be lesser than 0.5 i.e., hybrid system provides more than half of the required power from electrical power generated from internal combustion engine [13]. Batteries in hybrid system will be COTS product and the energy density of batteries are generally changing from 180 kWh/kg to 230 kWh/kg [4].

Based on UAM studies of Uber Elevate and TVF Working Group, mission profile, top-level requirements and technology assessment, top level requirements and specifications are determined as in Table 2.

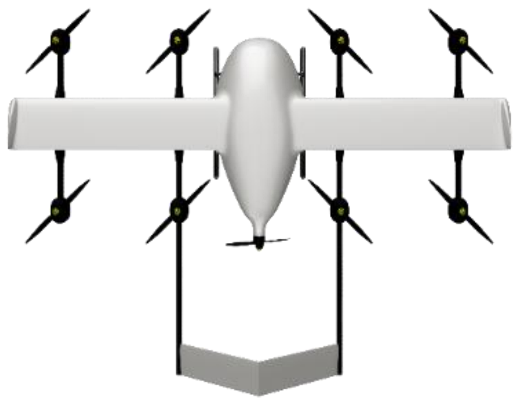

Figure 5. Selected Aircraft Configuration: Lift-Cruise

Table 2. Top Level Requirements and Specifications

Req. Name	Description
Design range	The design range must be equal to 100 km
Cruise speed	The cruise speed must be 180 km/h
Cruise altitude	The cruise altitude must be 5500 ft
Rate of climb	The rate of climb during climb phase must be 600 fpm
Rate of descent	The rate of descent during descend phase must be 1000 fpm
Passenger capacity	The aircraft shall carry the weight of 1 passenger
Powerplant systems	The aircraft shall have serial hyrid electric propulsion systems
Engine type	All propulsive engines shall be electrical
Redundancy	The aircraft shall have at least 6 propeller in vertical direction
Empennage configuration	The system must have V tail configuration with twin boom
Fuselage material	The material of the fuselage must be composite
Wing material	The material of the wing must be composite
Empennage material	The material of the empennage must be composite

3. SYSTEMS ENGINEERING METHODS AND MBSE

3.1. System Engineering Approach

General system engineering approach can be explained in Figure 6 as defined in report of Lightsey [17]. With given process input, requirements analysis, functional analysis and design synthesis phases are performed for the design of a system.

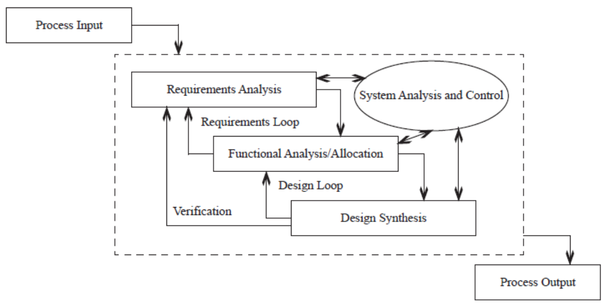

Figure 6. System engineering process [17]

The architecture described in Reference [9] and [10] is applied to the aircraft concept design cycle in this article. The detail architecture is shown in Figure 7.

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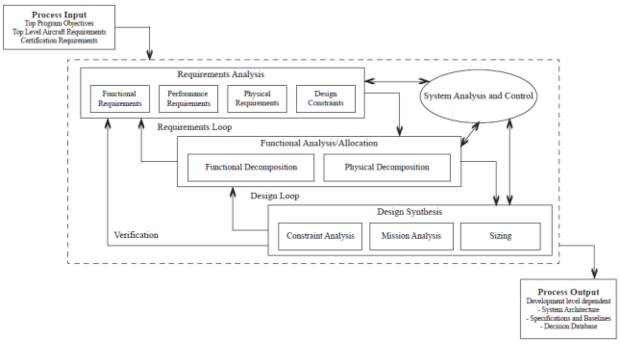

Figure 7. Concept Design Process with MBSE [9]

3.1.1. MBSE and SysML

The complexity of systems is increasing and managing this complexity is no easier with traditional system engineering approach. However, model-based system engineering is promising approach to manage this complexity. In the early of design phase, it enables to improve communication with customer and engineering team to be able to capture design needs.

To improve this communication with customer and engineering teams, both sides have to use same language. Therefore, MBSE generally use System Modeling Language (SysML) which is derived from Unified Modeling Language (UML).

4. MBSE APPROACH TO CONCEPTUAL DESIGN PROBLEM

In conceptual design process, constraint analysis and sizing studies are mainly performed using inhouse design tools scripted with Matlab/Python environment. These tools have lack of traceability of the design process when model-based system engineering is considered. Therefore, there must create a link between these tools and models generated with MBSE tools to provide the traceability in conceptual design process. This study is aim to handle conceptual aircraft design process with MBSE approach while also creating a link between inhouse design tools and MBSE tools. SysML is a common language in MBSE and MagicDraw is one of the modelling tool providing SysML usage. In this study, MagicDraw is using to model the design process.

Firstly, design process given in Figure 2 is modelled with SysML language as an activity diagram. Activity diagram of design process is illustrated in Figure 8. To identify the design process, subfunctions of these activities must be defined. Therefore, "Perform Conceptual Design" activity was detailed as seen in Figure 8. Subfunctions of "Perform Conceptual Design" are "Analyze Constraints" and "Perform Conceptual Aircraft Sizing". These activities correspond to general workflow of sizing process proposed in Figure 3. Detail of these activities are summarized in next sections.

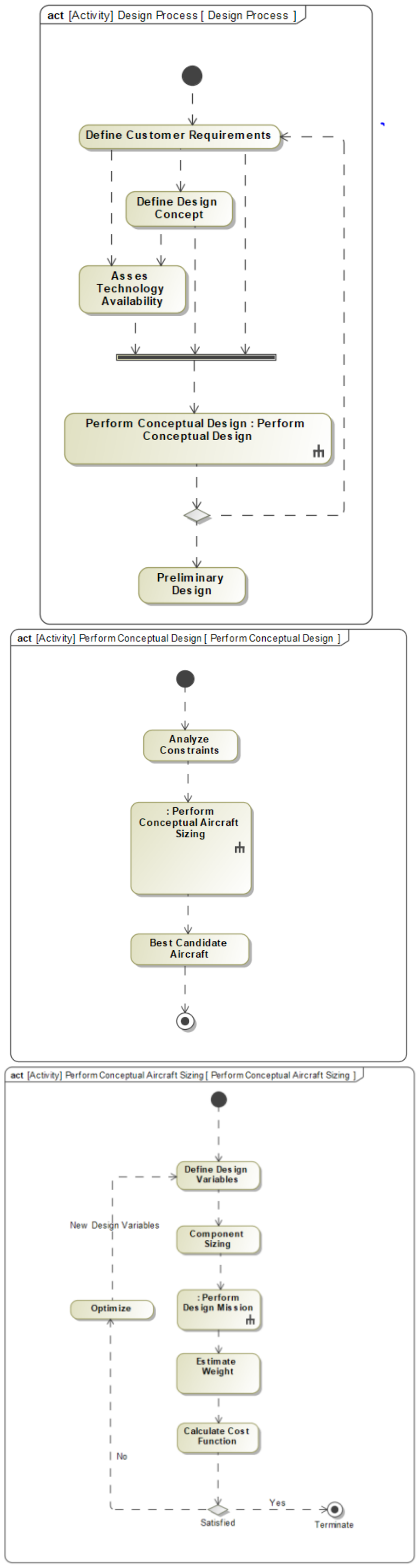

Figure 8. Workflow of design process

4.1. Constraint Analysis

Constraint analysis in aircraft design refers to the use of key aircraft flight profile conditions to constrain the loci of the allowable values for an aircraft's thrust to weight ratio and wing loading or disc loading [18][19]. In this study, constraint analysis is performed for winged flight i.e., it is used to size the wing and forward flight propulsion group of lift-cruise configuration. For winged flight conditions, thrust to weight ratio and wing loading is determined according to TLR with constraint analysis. For vertical flight of both configurations, thrust to weight ratio is selected as 1.5 to allow maneuvering margin with a failed motor.

4.2. Conceptual Aircraft Sizing Tool

In this sizing study, mass breakdown of aircraft and physical dimensions of the lifting surfaces (propellers, wing, tail) are estimated according to technology level of chosen subsystems of aircraft system modelled in the SysML. Conceptual aircraft sizing tool follows the design process given in Figure 3. This tool mainly consists of component sizing, performance analysis, weight estimation and optimizer modules.

Component Sizing module is used to size lifting surfaces (if A/C has lifting surfaces such as wing and tails) and propulsion group (electric motors) according to top level requirements and components' technology level for given MTOW. Aspect ratios of lifting surfaces are fixed and determined according to Reference [12]. For Lift-Cruise configuration, volume ratios of both tails are determined from Reference[12]. These parameters are also defined in SysML models.

Performance analysis module is used to calculate required power, burned fuel mass and required energy capacity for each mission segment[20][21]. Performance analysis is performed at steady state condition considering fuel burn.

Weight estimation module is used to estimate aircraft weight which includes various components such as lifting surfaces, fuselage, rotor, wire, avionics, internal combustion engine, generator, electric motors, battery, fuel and payload [18].

In aircraft sizing loop, optimization is also used to satisfy optimum design point. Since weight is a major concern for aircraft, minimizing MTOW is considered as an optimization problem. Constraints are used instead of nested inner iteration loops which used in estimation of MTOW, fuel mass, battery mass and engine mass [22].

4.3. Requirements Analysis

Requirement analysis is a phase that customer requirements are translated into system requirements. System requirements must define what system must do and how well it must perform [23]. System requirements can be divided as functional requirements, performance requirements, physical requirements and design constraint. Requirements are stored in requirement package as can be seen in Figure 9. Classification of requirements are also seen in the Figure 9.

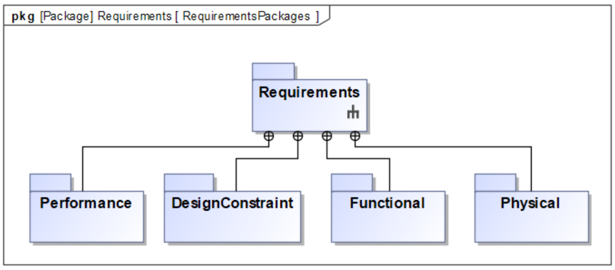

Figure 9. Classification of system requirements

Customer requirements are defined in the beginning of the design process. These requirements have to be analyzed for conceptual design process. Therefore, customer requirements are classified according to system requirements type as in the Figure 10.

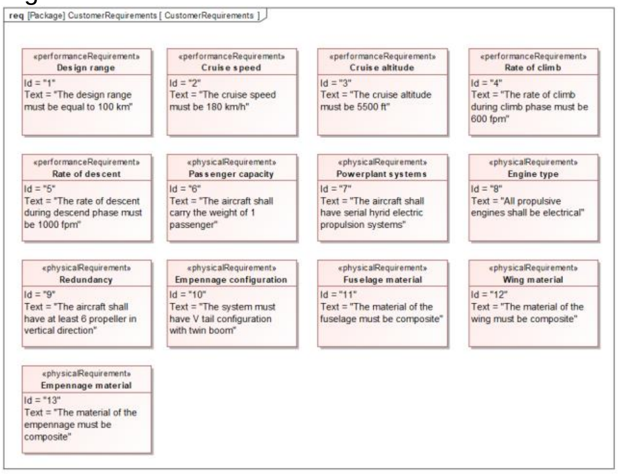

Figure 10. Customer requirements

The design constraints requirements check the objective and constraints of the aircraft sizing algorithms. An example of design constraints requirements is shown in Figure 11.

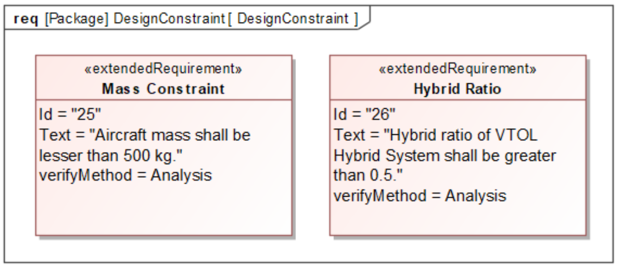

Figure 11. Design constraints requirements

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In the requirement analysis, the next step is to define use case. The top-level use case for VTOL aircraft system can be defined as to perform design mission. Therefore, “Perform Mission” use case element is created as seen in Figure 12. The actor in this use case is the person or payload who needed to transport with VTOL aircraft system.

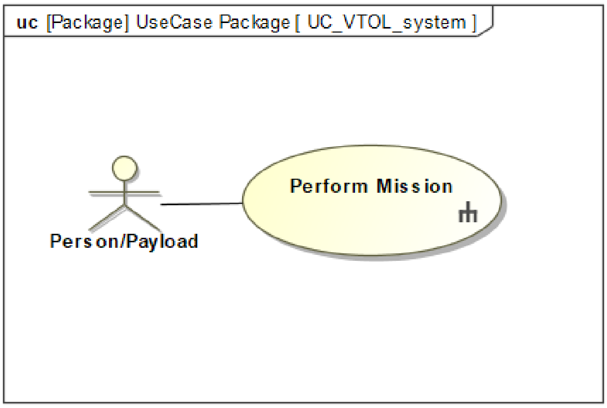

Figure 12. Use Case of VTOL aircraft system

After top level use case are defined, the use case is linked to associated performance requirements for traceability. The “trace” relation is used to link use case to requirements as seen in the Figure 13.

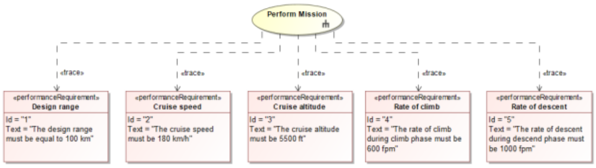

Figure 13. Traceability of use case

4.4. Functional Analysis/Allocation

Functional Analysis is a phase where the functional system requirements are transformed into a coherent description of system functions. Information about physical components of the system is also identified in the functional analysis and allocation process. In order to perform functional analysis and allocation, firstly, decomposition of top-level use case “Perform Mission” into functions are done. Functions of “Perform Mission” use case are shown in the Figure 14. These functions are the basic functions that are needed to size the aircraft system. Therefore, these basic functions can be assumed as the lowest level system functions for aircraft. In parallel of function decomposition, related functional requirement are defined. Functional requirements of VTOL system can be found in the Figure 15.

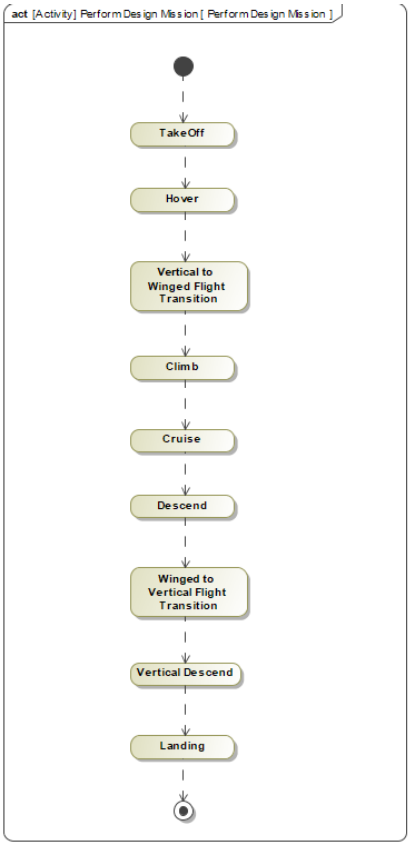

Figure 14. Functions of “Perform Mission”

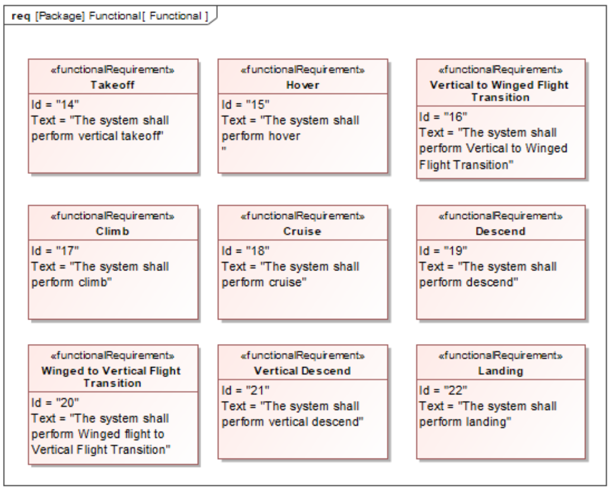

Figure 15. Functional requirements derived from aircraft system functions

After the functional decomposition are done, the physical components of the system, which are able to carry out these functions, have to be defined. To be define the subsystems of VTOL system, Joint Aircraft System/Component (JASC) Code table and definitions provided by FAA can be use [24]. When the subsystem of the aircraft is defined, the allocation of these required subsystem must be allocated to the basic functions of the aircraft system.

According to JASC Code, physical breakdown of the VTOL aircraft system is modeled with block definition diagram. Physical breakdown of the VTOL system is shown in the Figure 16. In this study, subsystems of the aircraft were defined simply enough to necessities of conceptual design. The allocation of these components with basic functions are done with using SysML Allocation Matrix. This allocation matrix can be seen in the Figure 17.

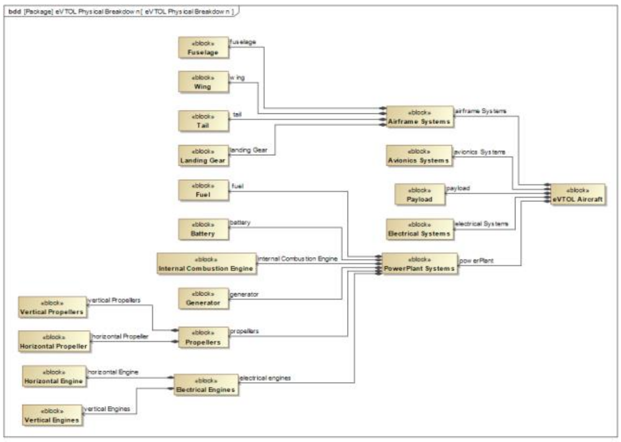

Figure 16. Physical breakdown structure of VTOL aircraft system

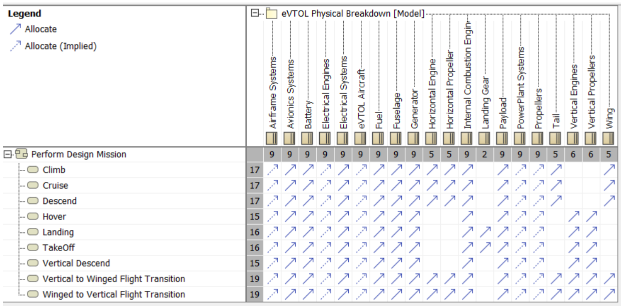

Figure 17. The allocation of components with basic functions

4.5. Design Synthesis

Design synthesis is a phase where physical architecture capable of performing the required functions within the limits of performance constraints is developed [23]. Generally, design synthesis consists of three subphases, which are architectural analysis (trade study), architectural design and detailed architectural design. However, this study aims to conceptual design of VTOL aircraft; therefore, the only architectural analysis (trade study) is applied in design synthesis.

Workflow of design synthesis for conceptual design study will be the same with “Perform Conceptual Design” activity defined in the design process (Figure 19). This workflow will be performed for different set of design variables to evaluate tradeoff of these variables. As an example, in this study, different battery subsystems were applied as a tradeoff.

Constraint blocks used in these diagrams are used to define mathematical expression and equations. Additionally, used for requirements verification in this study.

A link has been established between Cameo, which includes SysML models, and MATLAB, which includes sizing algorithms. In this connection, the output of MATLAB algorithms is converted to Excel/CSV format and Cameo models are updated with Excel/CSV outputs. The link structure realized between SysML model and Inhouse design tools is shown in Figure 18.

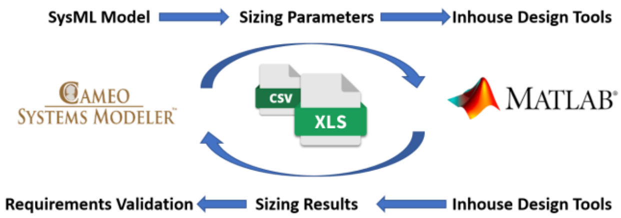

Figure 18. Link Structure

This update provides validation of requirements. With this link, an iterative design and validation cycle is created.

4.6. Requirements Verification

Design synthesis were executed with defined parameters of components and mission. In the result of these analyses, masses of all aircraft systems, geometrical properties of airframe systems such as wing and tail, required power for design mission were defined. Best candidate aircraft is available for this trade study. Now, these results can be validated with requirements. If all requirements can be satisfied in the conceptual design process, preliminary design process can be started to identify more details of aircraft system. The functional activity diagram of the perform concept design is shown in Figure 19.

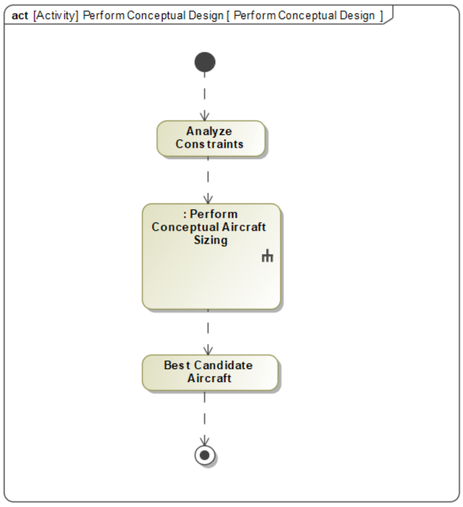

Figure 19. Workflow of design synthesis for conceptual design

In this study, as an example, the effect of different battery subsystem configurations on aircraft mass was investigated. Thus, aircraft mass requirement verification is performed. Requirement analysis and verification are shown in Figure 20.

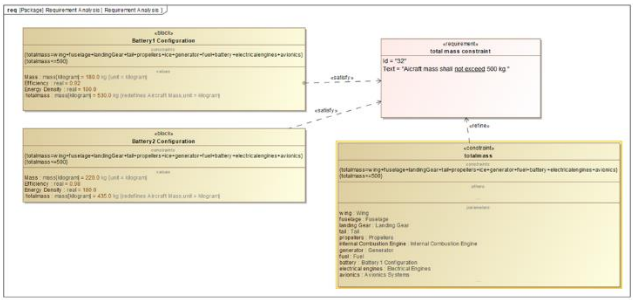

Figure 20. Requirements Analysis

Requirement verification is performed for two different battery configurations for hybrid electric VTOL aircraft.

Due to the low energy density of the Battery1 Configuration, the desired aircraft mass constraint could not be achieved. Requirements verification for Battery1 Configuration is shown in Figure 21.

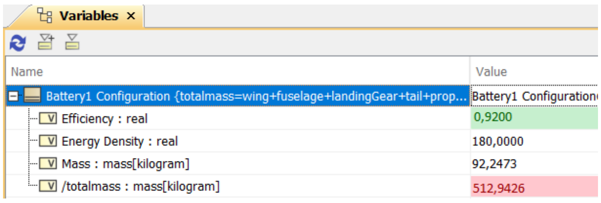

Figure 21. Battery1 Configuration Requirements Validation

Thanks to the high energy density of the Battery2 Configuration, the desired aircraft mass constraint was achieved. Thus, the battery to be used for the aircraft was selected. Requirements verification for Battery2 Configuration is shown in Figure 22.

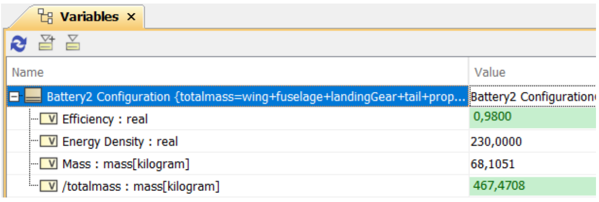

Figure 22. Battery2 Configuration Requirements Validation

5. CONCLUSION

In conclusion, the conceptual design of a hybrid propulsion e-VTOL system for intercity mission were performed with using MBSE approach. This study can be considered as a simple application of MBSE approach to the traditional conceptual aircraft design phase. It was aimed to understand how MBSE could increase the traceability of this design phase.

Firstly, customer requirements, mission profile, design concepts and available technologies were defined according to literature survey. From results of this survey, the system requirements for aircraft system were defined with requirement models in MagicDraw. Hence, MBSE approach to conceptual aircraft design problem was introduced. These processes were modelled as activities and shown with the activity diagram. For conceptual design of e-VTOL aircraft system, requirements analysis, functional analysis/allocation and design synthesis are performed. Moreover, in design synthesis, trade-off between different battery system was also performed. Here, the inhouse design tool was used to size the aircraft for different battery systems. The connection between inhouse design tool and MagicDraw was established with excel/csv file that keeps input and output parameters of design tool and design model in SysML. Verification of system requirements are done with sizing results of candidate aircraft generated as a results of design synthesis.

As a result of study, it was understood that MBSE approach can improve the traceability and generalization of the aircraft design process when compared to traditional design approach.

6. REFERENCES

[1] Kim, H. D., Perry, A. T., and Ansell, P. J. "A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology." *2018 AIAA/IEEE Electric Aircraft Technologies Symposium, EATS 2018*, 2018. doi:10.2514/6.2018-4998.

[2] Hoelzen, J., Liu, Y., Bensmann, B., Winnefeld, C., Elham, A., Friedrichs, J., and Hanke-Rauschenbach, R. "Conceptual Design of Operation Strategies for Hybrid Electric Aircraft." *Energies*, 2018. doi:10.3390/en11010217.

[3] Holden, J., and Goel, N. "Fast-Forwarding to a Future of On-Demand Urban Air Transportation." 2016, pp. 1–98.

[4] Datta, A. "Commercial Intra-City On-Demand Electric-Vtol Status Of Technology." 2018, pp. 1–57.

[5] Schömann, J. "Hybrid-Electric Propulsion Systems for Small Unmanned Aicraft." 2014, p. 178. doi:10.1504/IJTM.2004.004271.

[6] Fredericks, W. J., Moore, M. D., and Busan, R. C. "Benefits of Hybrid-Electric Propulsion to Achieve 4x Increase in Cruise Efficiency for a VTOL Aircraft." *2013 International Powered Lift Conference*, 2013, pp. 1–21.

doi:10.2514/6.2013-4324.

[7] Shamiyeh, M., Rothfeld, R., and Hornung, M. “A Performance Benchmark of Recent Personal Air Vehicle Concepts for Urban Air Mobility.” *31st Congress of the International Council of the Aeronautical Sciences, ICAS 2018*, 2018, pp. 1–12.

[8] Herbst, S., Wortmann, G., and Hornung, M. “Conceptual Design Studies of Vertical Takeoff and Landing Remotely Piloted Aircraft Systems for Hybrid Missions.” *CEAS Aeronautical Journal*, Vol. 7, No. 1, 2016, pp. 135–148. doi:10.1007/s13272-015-0176-x.

[9] Karagoz, E., Reilley, K. A., and Mavris, D. N. “Model-Based Approach to the Requirements Analysis for a Conceptual Aircraft Sizing and Synthesis Problem.” *AIAA Scitech 2019 Forum*, No. January, 2019. doi:10.2514/6.2019-0498.

[10] Bagdatli, B., Karagoz, F., Reilley, K., and Mavris, D. N. “MBSE-Enabled Interactive Environment for Aircraft Conceptual Sizing & Synthesis.” *AIAA Scitech 2019 Forum*, No. January, 2019, pp. 1–18. doi:10.2514/6.2019-0497.

[11] Fisher, Z. C., Daniel Cooksey, K., and Mavris, D. “A Model-Based Systems Engineering Approach to Design Automation of SUAS.” *IEEE Aerospace Conference Proceedings*, 2017. doi:10.1109/AERO.2017.7943597.

[12] Raymer, D. P. “Aircraft Design: A Conceptual Approach[Book].” *Washington, DC: American Institute of Aeronautics and Astronautics, Inc, 1992.*, 1992.

[13] Cakin, U., Kacan, Z., Aydogan, Z. A., and Kuvvetli, I. Initial Sizing of Hybrid Electric Vtol Aircraft for Intercity Urban Air Mobility. 2020.

[14] FAA. “FAR - AC 120-27F - Aircraft Weight and Balance Control.” Vol. 153, No. 9, 2009.

[15] Duffy, M. J., Wakayama, S., Hupp, R., Lacy, R., and Stauffer, M. “A Study in Reducing the Cost of Vertical Flight with Electric Propulsion.” *Annual Forum Proceedings - AHS International*, No. December, 2017, pp. 187–204.

[16] Finger, D. F., Braun, C., and Bil, C. “An Initial Sizing Methodology for Hybrid-Electric Light Aircraft.” *2018 Aviation Technology, Integration, and Operations Conference*, 2018. doi:10.2514/6.2018-4229.

[17] Lightsey, B. *System Engineering Fundamentals*. 2001.

[18] Gudmundsson, S. *General Aviation Aircraft Design: Applied Methods and Procedures*. 2013.

[19] Lewis, B. Constraints Analysis: Introduction. blewis.me/PP/intro.html.

[20] Johnson, W. *Helicopter Theory*.

[21] Anderson, J. D. *Aircraft Performance and Design*. 1999.

[22] Bower, G. Vahana Configuration Trade Study — Part II. https://vahana.aero/vahana-configuration-trade-study-part-ii-1edcdac8ad93.

[23] Hoffmann, H.-P. *Systems Engineering Best Practices with the Rational Solution for Systems and Software Engineering*. 2011.

[24] FAA. *Federal Aviation Administration Joint Aircraft System/Component Code Table and Definitions*. 2008.