A SEMANTIC MODEL-BASED SYSTEMS ENGINEERING APPROACH FOR SUPERSONIC BUSINESS JET CONCEPTUAL DESIGN

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Abstract

Supersonic business jet (SSBJ) is a complex system with more design constraints and higher performance demands. The conceptual design of supersonic business jet needs a comprehensive approach for its requirements, functions, logic, and physics. In this study, a semantic MBSE approach is developed for SSBJ conceptual design based on KARMA formalism. And a multidisciplinary design process is realized based on the metamodels developed for SSBJ conceptual layout, analysis, and simulation. The result shows the feasibility and effectiveness of the semantic MBSE approach on complex systems, heterogenous models, and interdisciplinary processes.

Keywords: MBSE, semantic modeling, aircraft conceptual design, supersonic business jet.

1. Introduction

Supersonic civil aircraft can decrease more than half of the flight time on intercontinental airlines, which makes it attractive to customers who attribute great value to time. However, due to the environmental and economic issues, especially sonic booms, there is no supersonic airliners in service since the retirement of Concorde in 2003. In recent years, with the advance of low drag, low boom, and efficient engine technology, it is hopeful that supersonic civil aircraft returns in service. Supersonic business jet (SSBJ) is a hotspot study object in aeronautic science and engineering because its potential customers usually value time than price and smaller size of aircraft enables lower sonic boom.

Conceptual design is the first and highly important phase of aircraft development. It involves multiple iterations, complex trade-offs, and critical decisions and determines more than 70% cost and technical feasibility of the life cycle[1]. A typical aircraft conceptual design process defined by Raymer is shown in Figure 1, where the designers look at a wide range of aircraft configuration concepts, perform trade studies of both the designs and the requirements, and ultimately settle on a single best design and, with significant customer input, select a well-balanced set of requirements[2]. There are already many study cases[3–5] on SSBJ conceptual design aiming on requirements, configuration layout, and characteristics of aerodynamics, sonic booms, flight performance, and etc.

However, current studies usually limit to requirements and physics of SSBJ, lack of more comprehensive viewpoints. With increase of system complexity, aircraft design involves remarkably more requirements, functions, and interactions. Especially, SSBJ has stronger coupling disciplines, more design constraints, and higher performances. And the realization of SSBJ is more dependent on functions of certain subsystems and adaptability to existing air traffic system. Therefore, SSBJ conceptual design should be led by a more comprehensive approach considering system of systems, missions, requirements, functions, logic, and physics. The industry standard "Development Process for Civil Aircraft"[6] divides aircraft design into five phases with eleven milestones which are defined with tasks and the exit criteria, shown in Figure 2. This standard stands on systems engineering viewpoints and highlights market, requirement, function, project management in aircraft conceptual design phase.

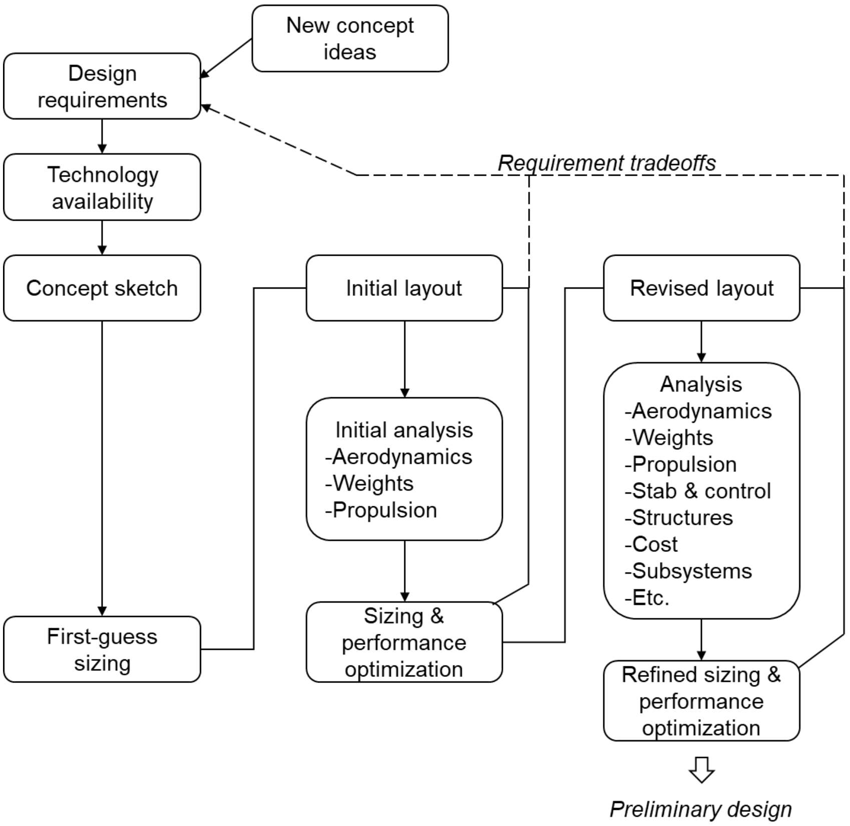

Figure 1 – Aircraft conceptual design process[2].

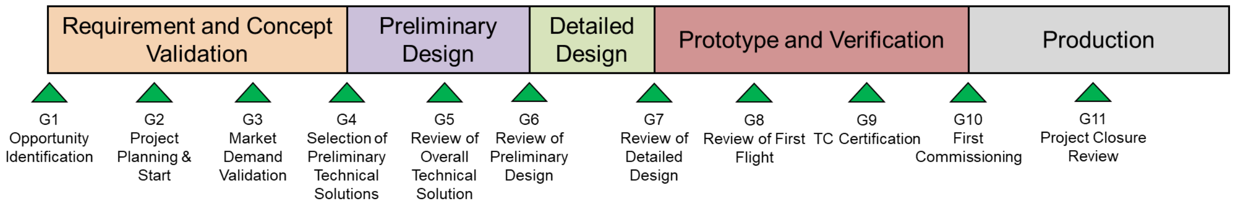

Figure 2 – Development process for civil aircraft[6].

In this paper, a semantic model-based systems engineering (MBSE) approach is proposed for SSBJ conceptual design, aiming to integrate requirement, function, logic, and physics of SSBJ in a unified formalism approach and eliminate the interdisciplinary heterogeneity, discontinuity, and non-interoperability. The paper is organized as follows: Section 2 presents a literature review of recent studies on aircraft conceptual design methodologies and cases; and analyzes the advantage of the semantic MBSE approach. Section 3 introduces the semantic MBSE approach for SSBJ conceptual design, including modeling approach and derivative capabilities. In section 4, the case study of an 8~10 seats SSBJ is presented. And section 5 summarizes the study and introduce further works.

2. Literature Review

2.1 Model-based Systems Engineering

Model-based systems engineering (MBSE) is the formalized application of modeling to support systems requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing through development and later life cycle phases[7].A distinguishing characteristic of an MBSE approach is that the model constitutes a primary artifact of the systems engineering process. The focus on developing, managing and controlling a model of the system is a shift from the traditional document-based approach to systems engineering, where the emphasis is on producing and controlling documentation about the system. By leveraging the system model as a primary artifact, MBSE offers the potential to enhance product quality, enhance reuse of the system modeling artifacts, and improve communications among the systems development team.

This, in turn, offers the potential to reduce the time and cost to integrate and test the system, and significantly reduce cost, schedule, and risks in fielding a system[8].

The critical enablers for MBSE include modeling languages, modeling tools and modeling methodologies. The most commonly used MBSE language for system requirement and architecture is System Modeling Language (SysML)[9]. SysML is a general-purpose graphical representation for the various disciplines of systems engineering. It was developed by the International Council on Systems Engineering (INCOSE) in cooperation with the Object Management Group (OMG)[10]. SysML consists of 9 different diagrams describing the requirements, structure, and behavior of the system and its components, supporting the specification, design, analysis, and verification of systems. It has been applied in the aircraft and its subsystem design in different researches[9, 11]. However, there are challenges for MBSE applications from data heterogeneity and non-interoperability between different languages[12], especially when there various customized domain-specific tools in aircraft conceptual design such as weight, aerodynamics, and flight performance. This makes it difficult to integrate requirement, architecture, and design of aircraft concept in a single modeling framework like SysML.

2.2 The Third Generation Multidisciplinary Design and Optimization

The third generation Multidisciplinary Design and Optimization (MDO) leverage distributed design tasks and competences to realize the collaboration between different engineers from distributed organizations. It can challenge the integration of an increasing number of systems and connected disciplines in aircraft design and find the overall benefit of novel concepts[13]. In AGILE project[14], the third generation MDO is developed for aeronautical systems collaborative development. Some design cases include conventional airliner, blend-wing-body aircraft, MALE UAV, and etc. The application of the third MDO framework achieves the reduction of 20% in time to converge the design of an aircraft and 40% in time needed to setup and solve the multidisciplinary problem in a team of heterogenous specialists.

Common Parametric Aircraft Configuration Schema (CPACS)[15] is the common language which describes aircraft conceptual and preliminary design for the third generation MDO. It is a text-based XML schema definition that can describe the geometry, performance, missions, and design space of an aircraft and integrate the connected information such as airports, airlines, flights, and design tools. Tools that support CPACS language can easily interoperate with each other and form an MDO environment. However, MDO usually aims to find the optimized parameters of the aircraft layout to reach the best performance of the system. And CPACS is a geometry-centric schema. It is still necessary to utilize other language such as SysML to describe requirements and architecture[16] and difficult to integrate both system function and performance design and verification in the third generation MDO framework.

2.3 Collaborative Design based on the Authoritative Source of Truth

The Authoritative Source of Truth (ASoT) captures the current state and the history of the technical baseline. It serves as the central reference point of models and data across the lifecycle. Providing ASoT across organizations is one of the goals of digital engineering strategy and is the key to shift the paradigm to model and data centric digital engineering ecosystem[17]. Based on ASoT, a collaborative design framework can be constructed for aircraft design, integrating design tools for different domains and advanced digital hardware such as high performance computers, virtual realities, and flight simulators[18, 19]. It provides a platform for designers of different roles and from different organizations to work together on consistent digital artifacts. Beihang University has researched on ASoT construction technology and application on aircraft design for years. Typical cases include unmanned combat aerial vehicles (UCAV) conceptual design[20] and civil aircraft concept research cooperating with Commercial Aircraft Corporation of China (COMAC)[21].

To realize collaborative design based on ASoT and get the benefit of data consistency, it is necessary to construct a common language for heterogenous models and data. A methodology for constructing the aircraft design schema (ADS) is proposed as a theoretical guidance to realize the common language and digital collaboration for aircraft conceptual design[22]. ADS is based on a meta-object facility (MOF) where the meta-data defines different data types and their attributes, providing an open and non-domain-specific data management framework. ADS supports multiple formats: A text-based JSON format as the standard data interface for ASoT system and design tools; and an Excel-based format for easier human reading and editing. ADS is the basic for ASoT system to realize data consistency such as version management, data trace, and design alternatives management. However, current ADS constructing methodology is too general and abstract to embody any domain-specific knowledge and characteristics, leading to the complexity of its construction and operation on different aircrafts. Additionally, ADS is a document-based schema without the ability to describe the complex relationships between different data. Its consistency needs to be ensured manually, which also increase the complexity of its operation.

2.4 Semantic Model-based Systems Engineering

Semantic MBSE is an approach that integrates semantic technologies and ontologies with MBSE methods. This method not only leverages the modeling advantages of MBSE but also enhances the expressiveness and interpretability of models through semantic technologies. Semantic MBSE captures and articulates various concepts and their interrelationships within system design by employing well-defined ontologies, thereby improving the precision and consistency of design information[23]. The advantages of semantic MBSE include its ability to provide a richer and more explicit data representation, facilitating effective communication and understanding of complex system designs among stakeholders from different domains. Additionally, semantic MBSE supports knowledge sharing, querying, and logical validation of design information, which helps to enhance design efficiency, ensure data consistency, and support system design and verification throughout the entire product lifecycle. Semantic MBSE also strengthens the capability for logical reasoning to support early requirement traceability and design decision-making[24].

The modeling language of semantic MBSE is mainly KARMA (Kombination of ARchitecture Model specification)[25]. The KARMA language is based on the GOPPRRE (graph, object, property, point, relationship, role, and extension) meta-meta modeling method. It offers a comprehensive representation of data and is used to construct domain-specific meta-model libraries that support the RFLP (Requirement, Function, Logical, and Physical) modeling process. There are various application cases of semantic MBSE across different fields, including but not limited to aviation[26], automotive, and smart manufacturing. For instance, in the aviation sector, semantic MBSE has been utilized to design an aircraft's Prognostic and Health Management (PHM) system[23]. By establishing a complete MBSE design process, an ontology model supporting the PHM system design was generated. Moreover, semantic MBSE has been applied in the field of smart manufacturing to support the design and optimization of manufacturing systems through ontology models[24].

3. Semantic MBSE Approach for SSBJ Conceptual Design

3.1 Overview of the Semantic Approach

Based the modeling language KARMA, a semantic MBSE approach for SSBJ conceptual design is proposed as shown in Figure 3. The KARMA language is developed based on GOPPRRE meta-metamodel and semantic specification instead of graphical specification. Using KARMA, metamodels are developed based on different modeling specifications, such as SysML or Modelica. For the representation of the SSBJ conceptual design, several modified SysML diagrams are defined to describe SSBJ mission profile, system hierarchy, geometry, and subsystem control logic. The KARMA language formalizes the metamodels and models based on a unified specification. Additionally, multidisciplinary process of SSBJ conceptual design can be integrated in KARMA modeling environment through static analysis and code generation. Property values can be captured to define formal constraints of the models through KARMA language, and then solver implements the calculation and static verification of the SSBJ concepts. Code can be generated based on rules defined to match certain metamodels and insert the properties into templates, and drives domain-specific tools to model, analyze, or simulate the SSBJ conceptual design beyond the semantic models.

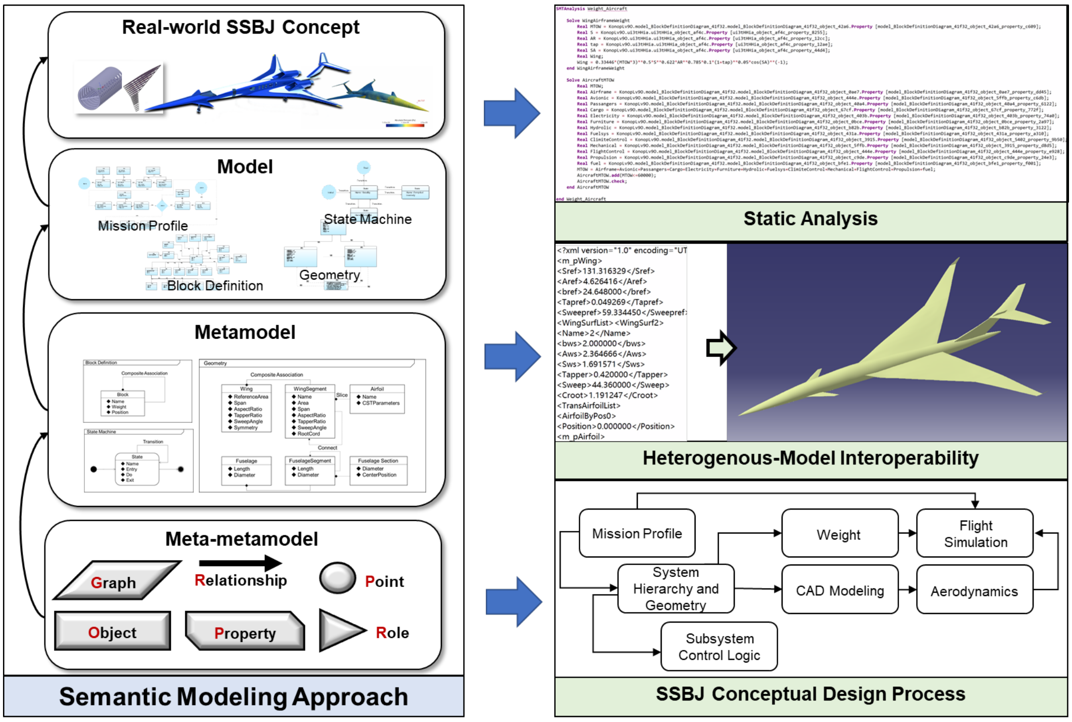

Figure 3 – Overview of Semantic Approach.

3.2 KARMA Language for SSBJ Design Modeling

3.2.1 GOPPRRE Formalism for Metamodel Development

GOPPRRE[27] formalism is the core of KARMA language. It is designed based on an MOF modeling framework that supports metamodel and model development. The MOF proposed by OMG provides an open and platform-independent metadata management framework and associated set of metadata services to enable the development and interoperability of model and metadata driven systems[28]. Four layers of MOF framework, M0-M3, are used to represent the SSBJ conceptual design using the semantic KARMA language to formalize the structure, behavior, and parameters of SSBJ using KARMA formalism.

- M3 refers to the meta-meta models, including the basic elements for developing metamodels based on the GOPPRRE concepts: (1) Graph; (2) Object; (3) Point; (4) Property; (5) Role; (6) Relationship; and (7) Extension.
- M2 refers to metamodels used for constructing models. In this study, metamodels are used to constructing the activities, structure and parameters of SSBJ and its subsystems. Their syntax and semantics are defined based mainly on SysML and are modified to represent aircraft geometry and mission performance and constrains better.
- M1 refers to models which describe the parameters, performances, and functions of SSBJ using graphical notations.
- M0 refers to the real SSBJ conceptual designs.

Based on the GOPPRRE formalism, the syntax of KARMA language can be used to describe metamodels and models of SSBJ conceptual designs. The details of GOPPRRE concepts are introduced as follows:

- ***Graph*** refers to a collection of ***Object*** and ***Relationship***. It is represented as one window referring to a model with graphical notations.
- ***Object*** refers to one entity in ***Graphs***. The entity could be a subsystem or a component of the aircraft, an activity or a constrain of the mission profile, or an airfoil or segment of the wing, depending on what the ***Graph*** is used to represent.
- ***Point*** refers to a port in each ***Object***.
- ***Property*** refers to one attribute in the other five non-property metamodels.
- ***Role*** refers to each end of ***Relationship*** used to define the connection rules for the relevant

Relationship. For example, one ***Relationship*** has two ***Roles***. Each is defined to connect one ***Point*** in ***Objects*** or one ***Object*** with the ***Relationship***. Then, the connector between the ***Relationship*** and the ***Points*** or ***Objects*** is created as a constraint to implement connections among different ***Objects***.

- ***Relationship*** refers to one connection between two ***Points*** of ***Objects*** or two ***Objects*** in a ***Graph***.
- ***Extension*** refers to the interrelationships among the six meta-metamodels, such as ***Graph*** contains ***Object*** and ***Relationship*** and one ***Point*** or ***Object*** connects with one ***Role*** in one side of the ***Relationship***.

3.2.2 Metamodels for SSBJ Conceptual Design

To support the formalism of SSBJ conceptual design, a set of metamodels with 4 graphs are developed in this study. The graphs are mainly based on SysML diagrams which describe system structure and behavior, and modifications are made for mission profile and geometry of SSBJ to simplify the modeling procedure. A detailed statistic of metamodels is shown in Table 1.

Table 1 – Metamodel numbers categorized by meta-metamodels.

Graph	Object	Point	Property	Relationship	Role
4	15	0	25	7	14

Mission profile of SSBJ is defined by an activity-diagram-like graph. Mission profile consists of a series of missions defined as actions with a start node and an end node with control flows connecting missions and nodes. Each mission has an altitude property and a Mach number property defined as arrays that describe the start and end status of SSBJ in the mission. To conveniently represent the mission constraints, a constraint object is defined in the graph with a constraint relationship to connect mission with constraint. Flight performance constraints such as acceleration, range, and take-off distance can be defined as a constraint object and connect to corresponding mission.

Block Definition Diagram (BDD) represents structural elements called blocks, and their composition and classification. Block is the object metamodel of BDD. And relationship metamodels includes composite association, reference association, generalization, and etc. In SSBJ conceptual design, BDD is useful to represent the system hierarchy of the aircraft with block and composite association metamodels. Meanwhile, the weight and position of the subsystems and components are the main concerns in aircraft conceptual layout. Hence, property metamodels include Weight, center of gravity, and Name are defined as the default attributes of blocks.

The geometry of the aircraft is the most important part of conceptual layout definition. The most commonly used geometric modeling method is based on the sections of surface. The components of the aircraft geometry can be classified as wing and fuselage, where the difference is the direction of the section normal. Wing surfaces usually include wings, horizontal and vertical tails, and canards, and their sections are parallel to the axis of the aircraft. Fuselages surfaces usually include fuselage and nacelles, and their sections are perpendicular to the axis of the aircraft. In this study, a modified BDD is defined to represent the aircraft geometry. The object metamodels are instantiated from block, including wing and fuselage surface, wing and fuselage segment, and wing and fuselage section. Some importance geometry parameters are defined as properties of these blocks. For wing surfaces and segments, it includes reference area, aspect ratio, tapper ratio, span, sweep angle, and etc. For fuselage surfaces and segments, it includes length and maximum diameter. Wing section (i.e., airfoil) is defined by Class-Shape-Transformation (CST) method. And fuselage section is circle defined by diameter and position of center. In addition to composite association representing the composition relationship between surface and segment, connect and slice are defined to represent the relationships between two segments (one connects with another) and between one segment and one section. Slice also has a position attribute to define the position of the section on the segment.

The control logic of subsystems of SSBJ is represented by state machine diagram (STM). The mainly used metamodels of STM in this study include initial pseudostate, state, and final state to represent the states of subsystems, and transition relationship to represent the transition between one state to another with trigger as its property to represent the event that causes the transition to occur. Figure 4 shows the metamodels defined in this study.

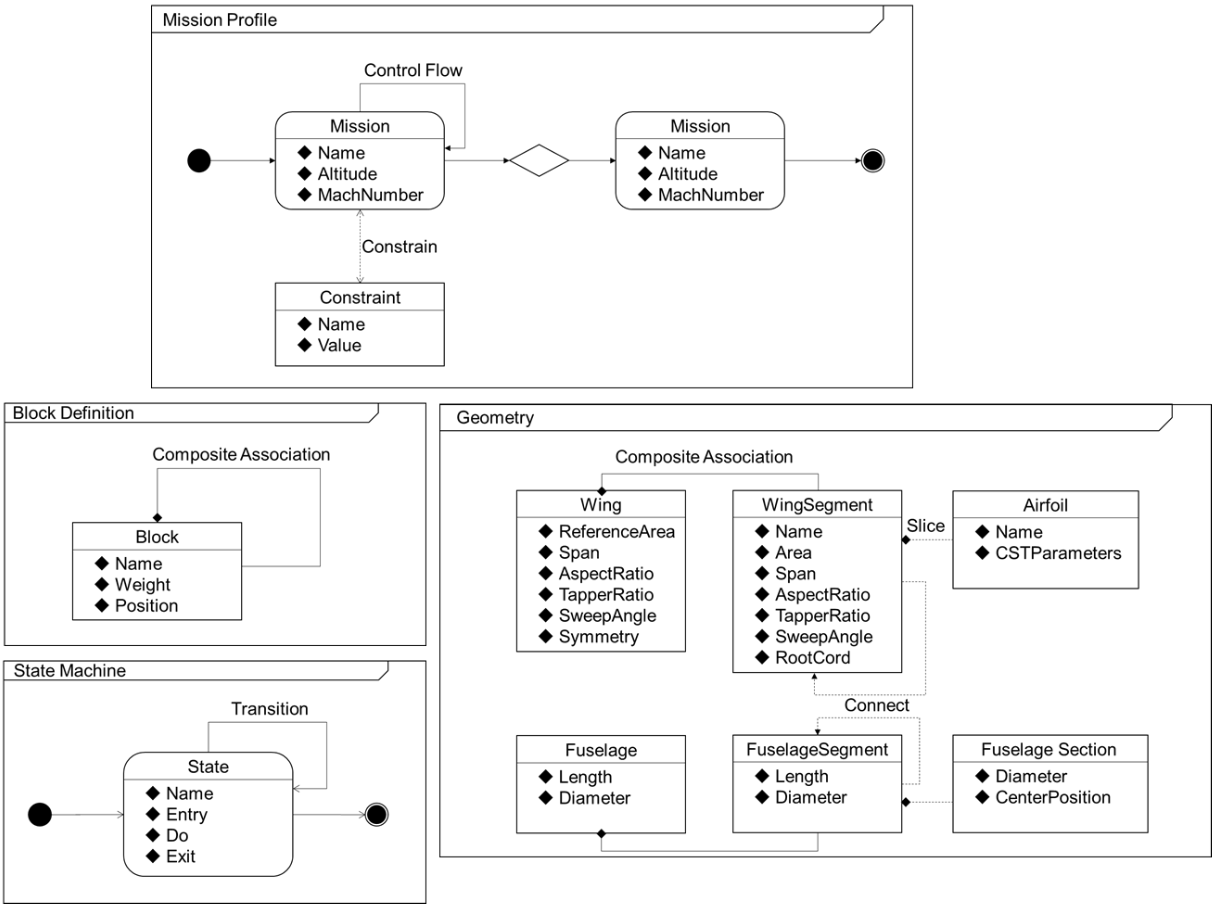

Figure 4 – Metamodels for SSBJ Conceptual Design

3.3 SSBJ Conceptual Design based on KARMA Formalism

Based on metamodels developed for SSBJ, the conceptual designs can be modeled within semantic approach. Then, KARMA formalism enables the design analysis and verification for the aircraft. Static analysis is used to calculate the parameter values of SSBJ and verify whether the parameters can satisfy the specified constraints. And heterogenous-model interoperability is used to execute domain specific models to address interdisciplinary problems in aircraft conceptual design.

3.3.1 Static Analysis for SSBJ Conceptual Design

Based on KARMA language, satisfiability modulo theories (SMT) are used to support the static analysis of SSBJ conceptual design, which refers to checking the satisfiability of logical formulas over one or more theories in the models combines the problem of Boolean satisfiability with some of the most fundamental fields in computer science. In addition, it draws on the most prolific problems in the past of symbolic logic: the decision problem, completeness and incompleteness of logical theories, and complexity theory[29]. The GOPPRRE method extended with SMT is used to solve the parameter attributes of SSBJ conceptual design and to test whether the logical constraints based on one or more mathematical theories are satisfied. In SMT solver, property values of the semantic models can be defined as parameters operating in mathematical calculation which is defined in the solver as well. Therefore, some basic parametric verification in SSBJ conceptual design is enabled in KARMA modeling environment, e.g., reference wing geometric parameters and aircraft take-off weight estimation.

3.3.2 Heterogenous-Model Interoperability for SSBJ Conceptual Design

Aircraft conceptual design is a multidisciplinary process involving domain-specific models which enable analysis and simulation that semantic models cannot support, e.g., computational fluid dynamic analysis. Hence the heterogenous-model interoperability of semantic model and domain-specific models is critical to realize SSBJ conceptual design. Code generation is the main enabler of model interoperability based on KARMA formalism. To realize code generation, rule class is defined in KARMA language to transform semantic models to specified text or other modes. A rule consists of three parts: matcher, template, and generator. As shown in Figure 5, matcher is used to locate models according to certain constraints, e.g., ID of metamodel; template defines the pattern of target code with text and placeholders; generator injects the information of the matched models into the template in the form of text and generates the corresponding code into a text file. Based on code generation, KARMA formalism can integrate different domain-specific tools with the semantic modeling environment, realizing interoperability of heterogenous models to address multidisciplinary problems in SSBJ conceptual design and ensuring consistency in different models. For example, geometric parameters of the SSBJ in semantic models can be used to generate parametric modeling scripts driving the tool in a CAD environment to generate a 3-dimensional geometric model of the aircraft.

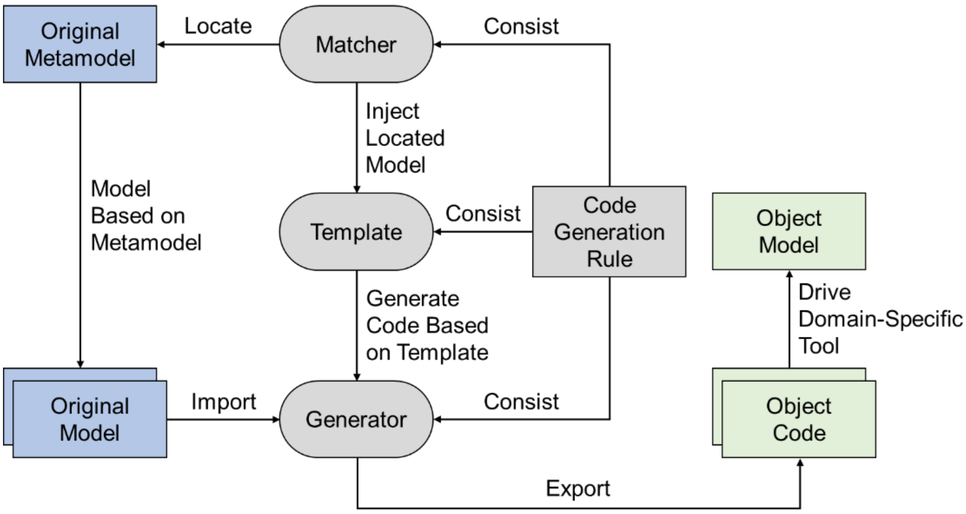

Figure 5 – Heterogenous-model interoperability based on code generation.

4. Case Study

4.1 Problem Statement

This study aims on an 8 to 10 seats SSBJ conceptual design cruising at Mach 2.0. The aircraft has a supersonic range more than 8000km to realize intercontinental flights across the Pacific and Atlantic Ocean. And the maximum range is more than 10000km to compete with currently popular subsonic business jets. The dimension and the take-off and land distance of the aircraft enables it adaptive to 4C or higher-rated airports.

In Beihang University, a team undergraduate thesis project involving different schools and disciplines was launched in 2022[19]. One of the goals of this project is to finish the SSBJ design and flight demonstration. In 2024, 44 teachers and 58 students from 9 schools of 3 universities involve in the project and design the conceptual layout, turbo engine, flight control, and enhanced vision system of the SSBJ. The dimensions of the SSBJ design result are shown in Figure 6 and some of the measurements of the design result are listed in Table 2. All the design objectives are satisfied and the low-speed scaled demonstrator is manufactured in July.

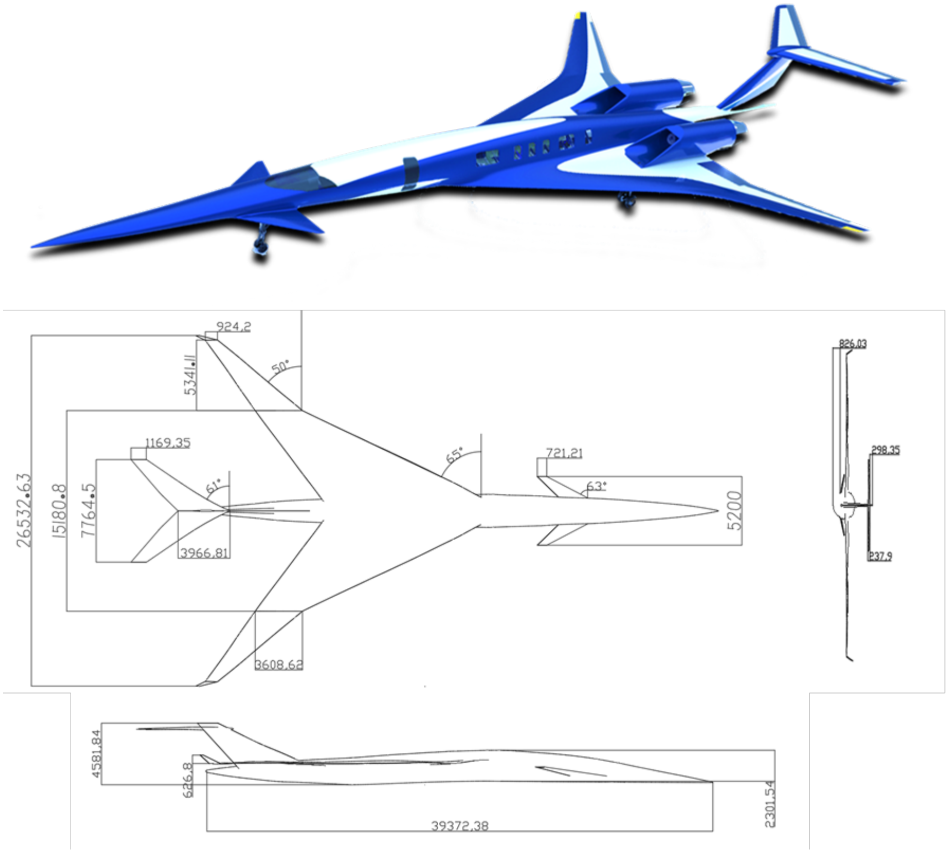

Figure 6 – Dimensions of the SSBJ design result.

Table 2 – Measurements of the SSBJ design result.

Measurements	Values
Maximum Take-off Weight	59300 kg
Supersonic Cruising Mach Number	2.0
Transonic Cruising Mach Number	0.9
Supersonic Range	8500 km
Maximum Range	11500 km
Classification of Airport	4C

In this study, the abovementioned SSBJ conceptual design is modeled based on KARMA formalism. Then with the semantic model, SMT analysis and code generation are performed to analyze the design and verify the requirements. Finally, an active center of gravity control system is designed in KARMA language and is simulated and verified based on heterogenous-model interoperability. The active COG control system changes the COG position of the aircraft by transfer of fuel in different tanks to reduce the supersonic cruise drag.

4.2 SSBJ Conceptual Design based on KARMA Formalism

Based on KARMA formalism, the SSBJ conceptual design is modeled in the semantic approach, including its mission profile and constraints, system hierarchy and geometry, and active COG control logic, shown in Figure 7. To be specific, the conventional airline flight mission and alternate landing with reserve range are both modeled in one mission profile diagram with a decision node to create branches for both missions. Then, system hierarchy is defined in a BDD with aircraft geometry as its decomposition diagrams. The weight and position information of all the subsystems and components are defined in the diagram as properties of block to analyze and verify the characteristics of aircrafts. Finally, the active COG control system is defined physically and logically. The flux and control logic of the pump are defined in a SMD.

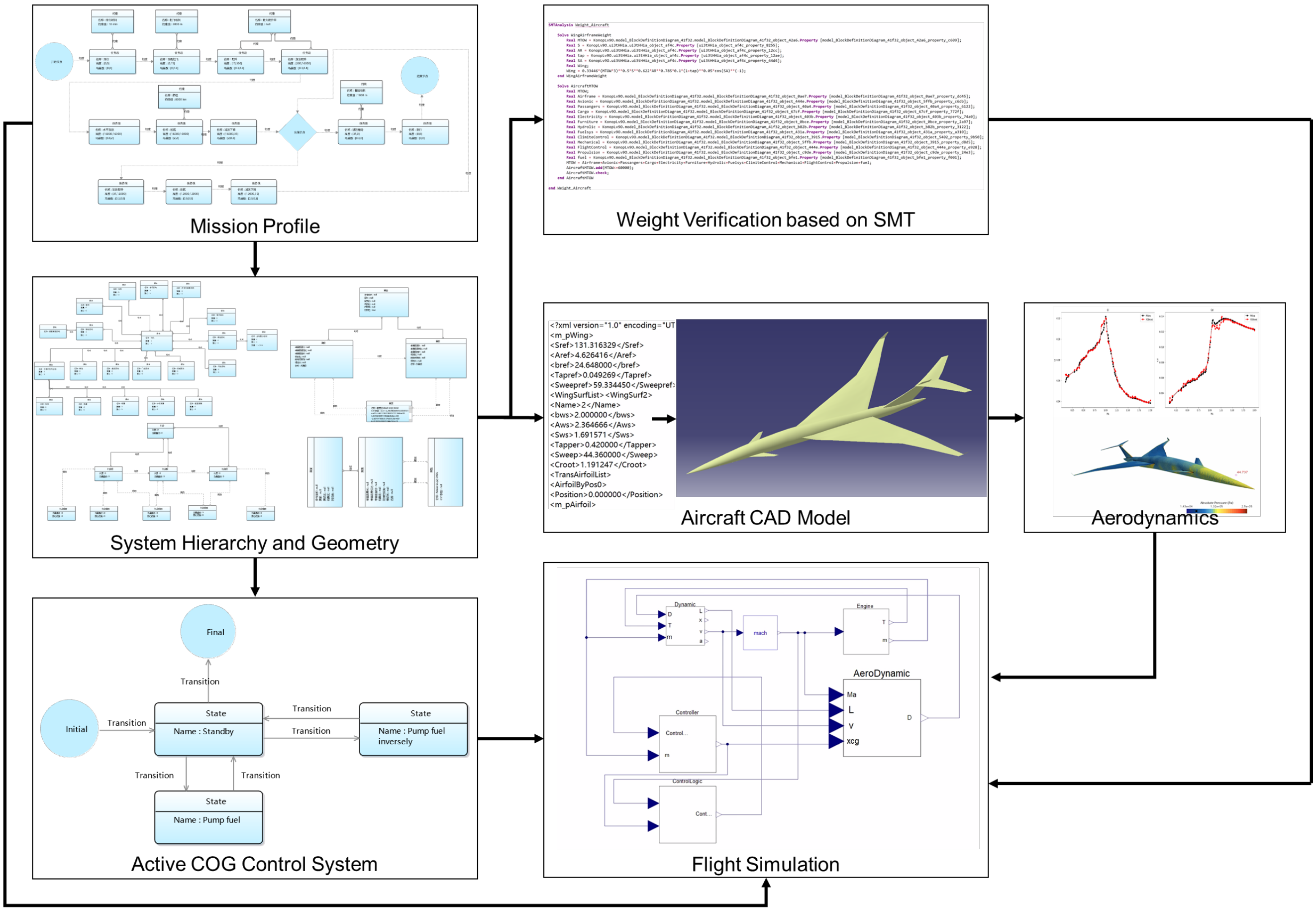

Figure 7 – SSBJ conceptual design process based on KARMA formalism.

As it is mentioned before that SMT analysis enables the calculation and verification of properties in KARMA modeling environment. The evaluation of weight and COG is performed with engineering estimation which is suitable for SMT analysis. Two SMT solvers are defined in the SSBJ conceptual design models: one is defined based on engineering estimation formula to analyze airframe weight from geometric parameters; the other one analyzes the maximum take-off weight and COG of the aircraft based on weight and position of airframe and subsystems.

Aerodynamics of the SSBJ is analyzed based on computational fluid dynamics (CFD). In this study, a parametric shape modeling tool is driven by scripts from code generation, as shown in Figure 8. The scripts are in XML format and is defined with all the geometric parameters needed for shape modeling. Then, geometry model in general format such as *.igs* or *.stp* is converted by modeling tool and is used to generate mesh and perform CFD analysis.

The active COG control system is composited by a fuel pump and two tanks on different positions in the wing which have been defined in the system hierarchy model. When the SSBJ is operating, the COG control system adjusts the COG of the aircraft by pumping the fuel between two tanks. Hence the static stability margin can be controlled in a certain range to reduce the drag force. As shown in Equation 1, $\bar{x}_{WB}$ and $\bar{x}_T$ are aerodynamic center of wing-body and tail, $\bar{x}_{cg}$ is the COG of the aircraft. The rate of COG change is shown in Equation 2, where ρ is the density of fuel, Q is the flux of the pump, and Δx is the distance between two tanks on the direction of aircraft axis. The active COG control system adjusts the COG to offset the influence of the COG change with fuel consumption and aerodynamic center change with flight velocity, to realize benefit such as reduce of fuel consumption and extension of range.

$$C_D = C_{D0} + K_{WB}\left(\frac{\left(\bar{x}_T - \bar{x}_{cg}\right)C_L - C_{mz0}}{\bar{x}_T - \bar{x}_{WB}}\right)^2 + \frac{S_T}{S}K_T\left(\frac{S}{S_T}\left(C_L - \frac{\left(\bar{x}_T - \bar{x}_{cg}\right)C_L - C_{mz0}}{\bar{x}_T - \bar{x}_{WB}}\right)\right)^2 \qquad (1)$$

$$\frac{d\bar{x}_{cg}}{dt} = \frac{\rho Q \Delta x}{mg \bullet MAC} \tag{2}$$

For active COG control system, a simulation of fixed-altitude acceleration from subsonic to supersonic is achieved in a Modelica tool to verify the benefits of active COG control system on reducing the aerodynamic drag force while the aerodynamic center of the aircraft is moving with its acceleration. A predefined model library is used in this case, including aircraft dynamic equation, engine thrust and fuel consumption, and aerodynamic interpolation. The code that calls the library and defines control logic and simulation boundary conditions is generated from semantic models of the SSBJ: altitude and start and end velocity from mission profile model; the start status of weight and COG from system hierarchy; and the flux and control logic of active COG control system from STM. Figure 9 shows the drag force on different Mach number with different pump flux. The result shows that the drag force reduces on different Mach number with the increase of pump flux.

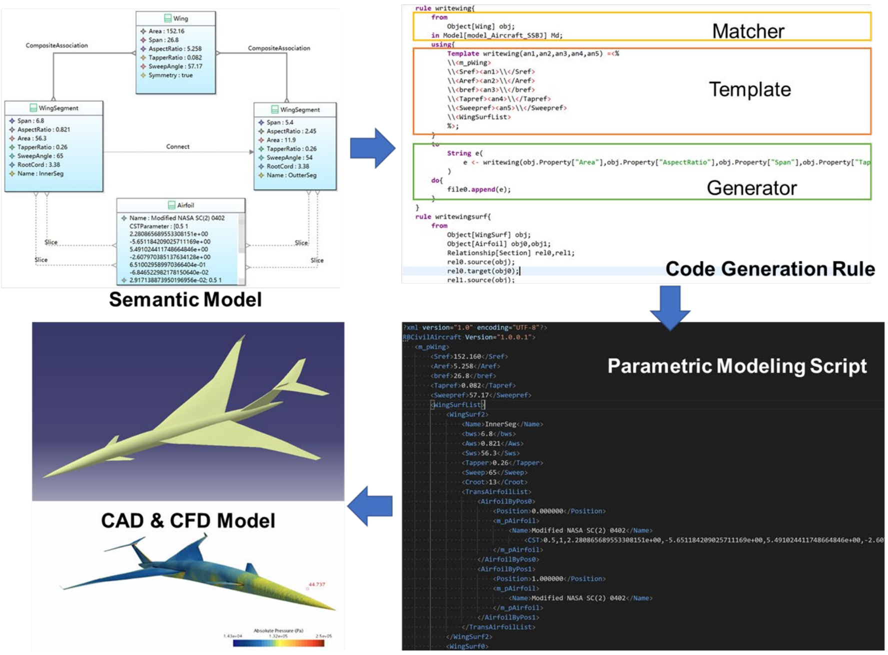

Figure 8 – Code generation for aircraft geometry.

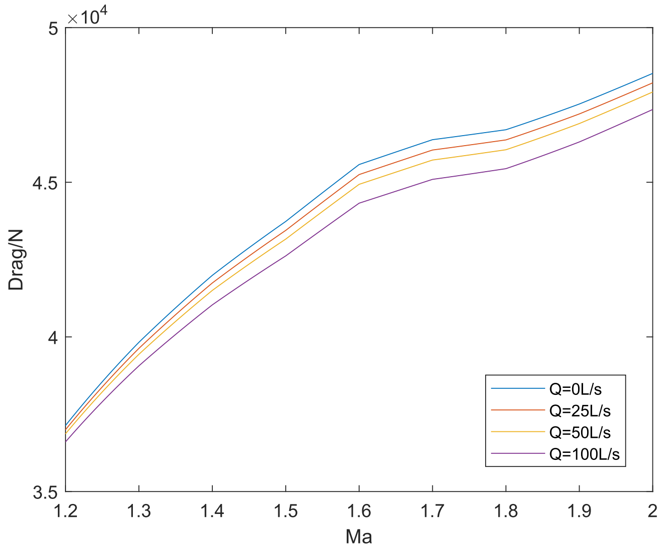

Figure 9 – Aerodynamic drag on different Mach number.

5. Conclusion and Future Works

In this study, a semantic MBSE approach is proposed for SSBJ conceptual design. Metamodels are developed based on KARMA formalism and semantic models are developed to represent the mission profile, system hierarchy, geometry, and subsystem control logic. The semantic representation is mainly based on SysML with modifications to simplify the modeling process for SSBJ conceptual design. Then, based on SMT analysis and code generation, analysis, verification, and heterogenous-model interoperability are realized to integrate multidisciplinary process in KARMA modeling environment, including weight analysis and verification, CAD modeling and aerodynamic analysis, and flight simulation for active COG control system based on Modelica. The main contribution of this study is realizing an aircraft conceptual design process across system hierarchy and RFLP based on semantic modeling approach, offering a comprehensive viewpoint to SSBJ conceptual design and following the development trends of system complexity and aircraft conceptual design. And it shows the feasibility and effectiveness of the semantic MBSE approach on complex systems, heterogenous models, and interdisciplinary processes.

The future works will mainly concentrate on two aspects: On KARMA formalism. the extension meta-metamodel will be refined to represent more modeling constraints. Hence metamodels will contain more domain-specific knowledge to reduce potential burden and mistakes in modeling. For example, every segment of a wing or fuselage must have at least two sections on both ends of the surface. With the constraint defined in metamodel semantics, the geometry can be automatically modeled and checked. Meanwhile, on the SSBJ conceptual design approach, more metamodels will be developed based on SysML and Modelica specifications, and system of systems modeling specifications, e.g., UPDM, will be added into the semantic approach to a more comprehensive requirement trade-off and verification on aircraft adaptability, maintenance, reliability, and etc.

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7. Copyright Statement

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